WANL-L-199
June 15, 1967

Westinghouse Astronuclear Laboratory

TECHNICAL PROGRAM SUMMARY
OUT-OF-VACUUM ELECTRON BEAM WELDING

Astronuclear Laboratory

WANL-L-199

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TECHNICAL PROGRAM SUMMARY

OUT-OF-VACUUM ELECTRON BEAM WELDING (March 1966 through April 1967)

Contract NAS 8-11929

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INFORMATION CATEGORY
Unclassified
J. M. Hungerley 8/18/67
AUTHORIZED CLASSIFIER DATE

Prepared for the George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

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Astronuclear Laboratory

ABSTRACT

This welding development study established the operating characteristics and penetration limitations of the NASA-15 KVA Out-of-Vacuum Electron Beam Welder. Using this equipment, operating parameters and their effects at high power input levels were explored to further define overall process capabilities.

The maximum weldable thickness, while maintaining a practical latitude in weld speed and energy control requirements, was established as approximately 0.712 inches. Radiographic quality could not be achieved in these heavier materials but reduction in weld speed to very low values (10-12 inches/min) did produce considerable improvement in 1/2 inch plate. Consistent reproducible radiographic quality to the requirements of ABMA-PD-R-27A, Class II was achieved on 1/4 material at 45 I.P.M. weld speed. Tensile and bend testing were conducted on a series of welds produced with these conditions.

Utilizing the maximum power available in the NASA welder and operation at short gun to work distance reduced heat input to 10.5 kilojoules/in./in. with aspect ratios of 1.6/1 on 1/4 inch plate material. Modifying effluent gas flow from the gun improved performance and resulted in what has been defined as "the narrow weld phenomena" which made possible the production of welds at even lower heat input (8.4 KJ/in./in.) and increased weld depth to width ratio to 2.5/1. Ultimate tensile strengths to 49,000 PSI were produced in these narrow welds. Control of this weld narrowing ability could not be achieved on heavier material (0.350 in. and 0.500 in.). It was apparent that more thorough understanding of what is actually taking place is essential to the most effective application of this phenomena.

Welding in a controlled atmosphere chamber demonstrated that porosity occurred in higher speed welding even with a closely controlled shielding environment. However, modifying effluent gas flow to achieve narrower welds also resulted in the production of void free joints modifying weld speeds.

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1. INTRODUCTION

During 1965 contract NAS 8-11929 was initiated between NASA Marshall Space Flight Center (Welding Engineering Branch) and the Westinghouse Electric Corporation. Phase I of this contract involved a welding engineering study of basic parameter relationships in out-of-vacuum electron beam welding. Phase II required the construction of a light weight, portable non-vacuum electron beam welding head, manipulator and enclosure. This report details work conducted as part of the Phase I program.

The initial tasks (A and B) of the welding engineering study were conducted with an available laboratory unit which had a limited power output. The results of this work were reported in a Technical Progress Summary (Relationships Between Weld Quality and Non-Vacuum Electron Beam Welding Quality) issued February 1966. In addition to evaluating many basic weld parameters, this earlier work demonstrated that the higher power available in the equipment built for NASA would considerably extend the application of the process.

To evaluate the increased power input and the effects on overall welding capability and weld quality, additional funding was provided to extend the Phase I study using the NASA 15 KVA welder and power supply. Tasks C, D and E were conducted under the expanded scope of this program.

1.1 SCOPE

To demonstrate the capabilities of the 15 KVA out-of-vacuum electron beam welder, approximately 600 test welds were produced on 2219-T87 aluminum alloy. These welds, in a number of material thicknesses, were made with a wide variety of operating parameters. This report details the findings of this study which was divided into the following series of experiments:

Task C - Various material thicknesses (.250, .350, .500, .712, .832) of 2219 aluminum were welded to establish the maximum weldable thickness using the 15 KVA weld gun. Porosity occurrence on all thicknesses was related to specification ABMA-PD-R-27A. Mechanical testing, tensile and bend, was performed on a series of 1/4 inch plate welds produced with parameters which gave consistent porosity free joints.

Task D - Using the full power capability of the NASA welder, minimum energy input welds (the most favorable time temperature condition) were produced in 1/4 inch, 2219-T87 aluminum plate material. Strength and weld configuration were evaluated in these welds in addition to the relationships to gas flow conditions.

Task E - Porosity occurrence and its possible source in high speed welding by the Out-of-Vacuum Electron Beam Process were determined.

1.2 MATERIAL

Material for the program was 2219 aluminum alloy furnished in the T-87 condition. The nominal chemical analysis of this material is as follows:

Element	Percent	Element	Percent
Si	.20 Max	Zn	.10 Max
Fe	.30 Max	Ti	.02/.10
Cu	5.8/6.8	V	.05/.15
Mn	.20/.40	Zr	.10/.25
Mg	.02 Max	Other Total	.15 Max

Base metal strength was established for all those thicknesses and groups on which weld tensile properties were evaluated. These results were as follows:

Identification	Thickness (Inches)	Ultimate Tensile Strength (psi)	Yield Strength (0.2% Offset) (psi)	Elongation (% in 2 in.)
2	.250	68,380	54,545	10.5
2A	.250	68,390	54,010	12
3	.250	66,400	53,240	13.5
5A	.250	66,730	53,520	14.0
4	.500	70,300	48,500	10.5
4A	.500	70,300	50,000	9.5

1.3 EQUIPMENT

1.3.1 Welder

The primary welding effort on this program phase was conducted using the 15 KVA out-of-vacuum Electron Beam Welder built for NASA-Marshall Space Flight Center. This unit, designated the XWEB 15121, is shown in Figure 1. Powered by a 15 KVA, 150 KV supply, which is driven by a 400 cycle, 280 V generator, the welder is of a unique compact design. The power supply and welding gun, complete with all high vacuum pumps and accessories, are assembled into a 210 lb (approx.) assembly that can be mounted in either the down-hand or horizontal welding position. This assembly is mounted on a conventional side beam carriage. Flexible low vacuum lines permit the welding head to be traversed four feet in a straight line while connected to the floor mounted controls and low vacuum pumps. The complete unit is enclosed in a lead shielded room for X-ray protection.

Electron emission from an indirectly heated tungsten rod is focused through differentially pumped orifices by a combination of electrostatic and electromagnatic electron optical systems. A wide variety of operating power levels of the electron beam are available over a broad range of amperage and accelerating voltages; up to a maximum of 80 Ma at 150 KV. A positive pressure is applied at a gas protection orifice which is located just below the exit orifice of the gun producing an effluent flow from the gun. This protection system minimizes contamination of the vacuum system. Introduction of helium into the gun, as was done in all these weld tests, also assures minimum interference with the beam by the gas in the transfer system.

The mechanical drive system of the welder was capable of moving the welding head at speeds up to 140 inches/minute. Higher welding speeds (up to 280 inches/minute) were achieved by driving both the work and the welder in opposite directions. As required, the work was mounted on a rack and pinion-driven cart.

A series of weld tests conducted in a vacuum and controlled atmosphere chamber were performed using a 10 KVA laboratory unit shown in Figure 2. The electron emission, gun column, beam focusing and gas protection system of this equipment are essentially the same

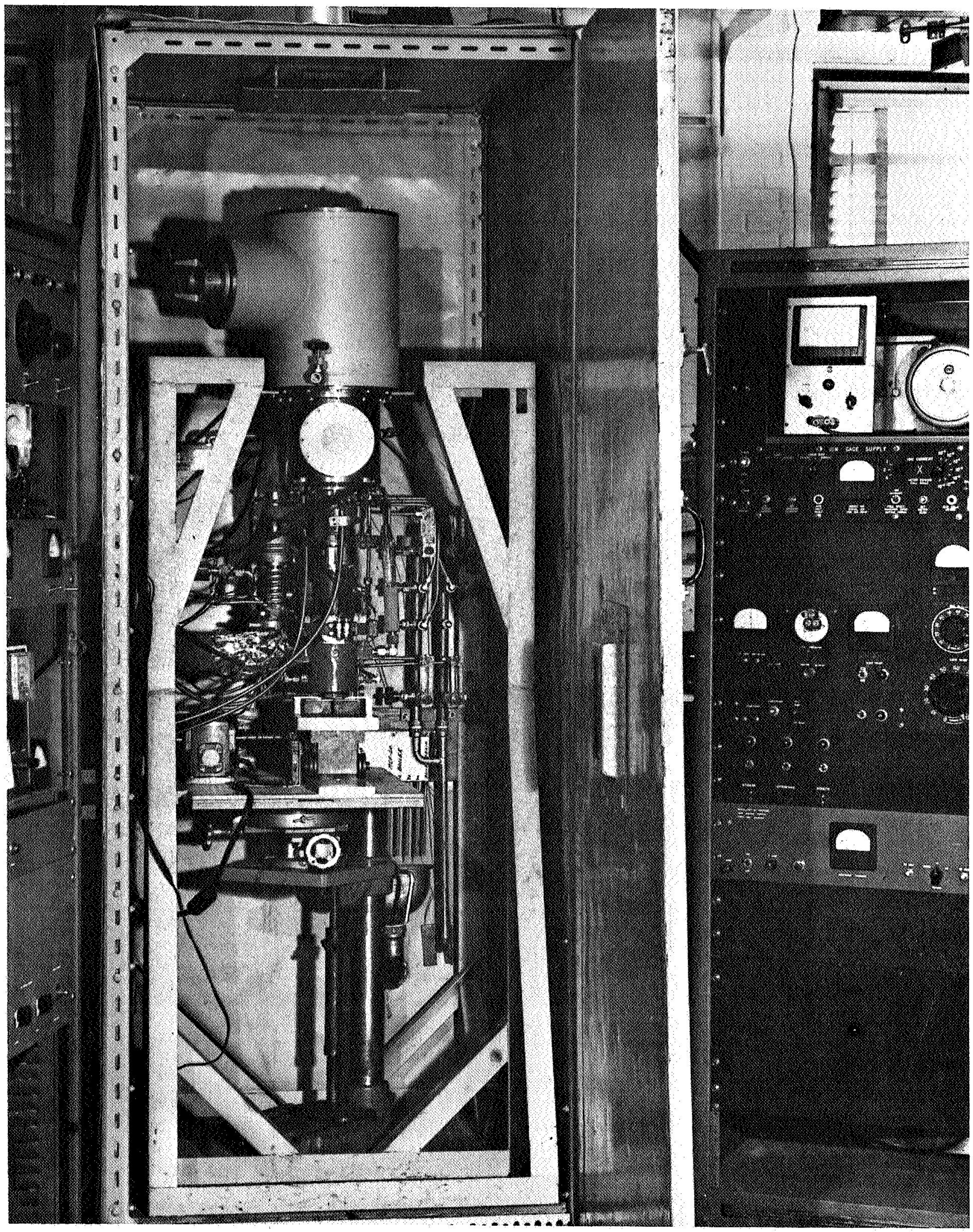


Figure 1. Westinghouse 10 KVA Laboratory Welder Used for Tasks A and B

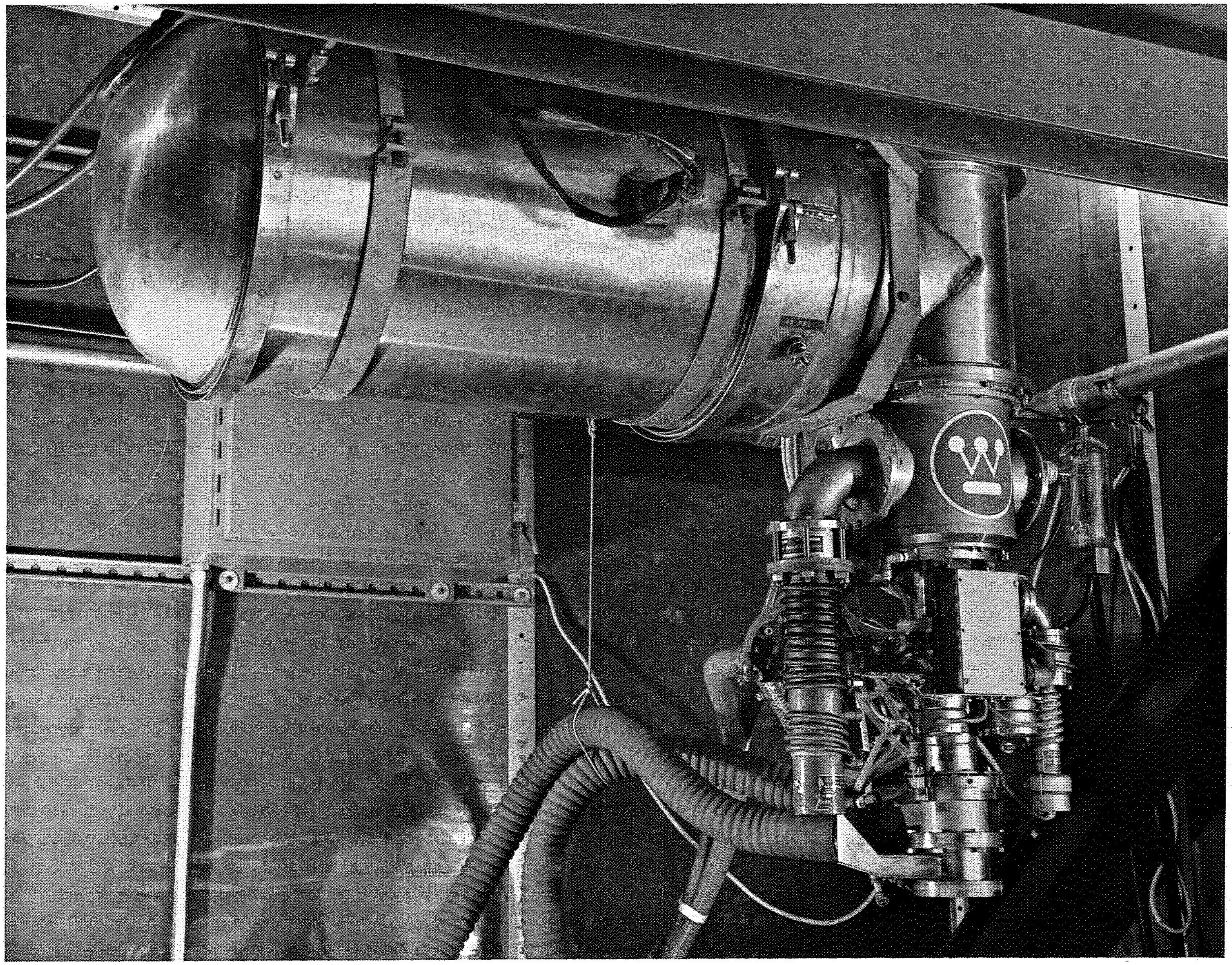


Figure 2. 10 KVA Laboratory Unit

as the previously described welder. The only difference is that this unit is a stationary device designed to test development components at somewhat reduced power levels. The chamber in which the tests were conducted was attached directly to the bottom plate of this gun column.

2. TEST PROCEDURES

2.1 GAS MONITORING AND CONTROL

Since a primary purpose of the weld program was an evaluation of porosity under a variety of parametric conditions, all gas systems associated with the welder were modified and monitored to assure consistent, high purity operation. The gas protection system in the gun, for these tests, employed nitrogen, during standby periods, and helium during actual beam operation time. All copper tubing was installed on fixed gas lines for this system and the flexible lines to the gun were converted to poly vinyl chloride tubing. Monitoring of the moisture content of the effluent gas flow from the gun, after the improvements, showed 4 PPM of H_2O in the nitrogen and 5 PPM of H_2O in the helium. The gas could be checked even during actual beam operation time using the setup shown in Figure 3. All lines providing face and backup shielding as required were improved in a like manner to assure a maximum ability to limit weld contamination.

The helium gas employed in this program was purchased as 99.995 percent grade with the following guaranteed contaminant levels:

N_2	-	.003% Max
O_2	-	.001% Max
Ne	-	.0007% Max
CO_2	-	.0007% Max
Ar	-	.0001% Max
H_2	-	.00005% Max
CO	-	.00005% Max
H_2O	-	-90° Dew Point Max

All individual gas bottles were tested for moisture content using a CVC Type 26-303 Moisture Monitor. The nitrogen employed was of a similar quality level and was also monitored on a periodic basis to assure consistent low moisture content.

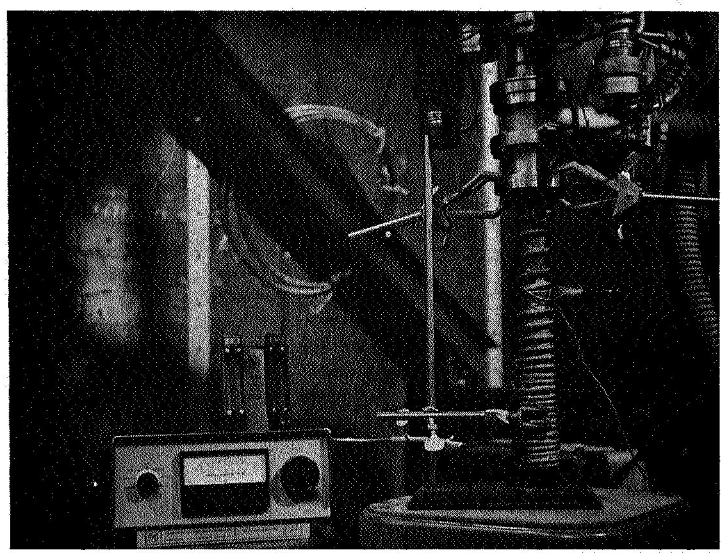


Figure 3. Monitoring the Moisture Level of Effluent Gas Flow

The gas and electron beam enter a sealed water cooled copper collector. Exit gas from the collector is carried through the CVC-Moisture Monitor.

2.2 GUN OPERATION

Certain basic gun operation techniques were established to assure maximum reproducibility of data. Power loss, or attenuation of some portion of the electron beam, occurs in the transfer section of the out-of-vacuum electron beam equipment employed in this type of experimentation. Thus, the actual transmitted current or power level striking the work at a given voltage becomes the most important parameter for data correlation. This power is determined by running the beam into a water cooled copper cup (Faraday Cup) and weld conditions established by measuring transmitted current immediately prior to making a weld.

Tests conducted in earlier work phases (see: Technical Progress Summary: Relationship Between Weld Quality and Non-Vacuum Electron Beam Welding Procedures, February 1966) had indicated that a minor weld effect did occur with changes in focus current. High current adjusts the point of minimum beam diameter upward or further into the gun. Conversely, low focus current adjusts the focus point downward or closer to the outer plate of the welder. The limit of this adjustment is related to the beam size at the orifice location or, in terms of parameters which are measureable on the welder instrumentation, transmitted current and maximum temperature at No. 2 orifice. To standardize for these tests, the focus current was adjusted for maximum transmitted current at a given input power level. This point, incidently, always resulted in the minimum temperature at the orifice. This approach, taken in early work, was proven sound during weld tests at high power levels. At the higher powers, the usable range of focus currents was narrow.

2.3 FIXTURE AND CLEANING

A stainless steel weld fixture was employed for holding the workpiece. A variety of backup bars or backup gas could be used with this fixture. Many of the test welds were bead-on-plate types in which no hold-down was required. Hold-down to the fixture was also not required on low speed butt welding of all material thicknesses. At high welding speeds it was necessary to clamp the material to the backup. Tacking was also necessary on all 1/4 inch plate butt joints to assure consistent joint opening and thus weld configuration. Tacks were made by using the welder to fuze short lengths on either end of the joint.

Earlier weld tests had demonstrated the effectiveness of mechanical cleaning of the workpiece for removal of surface contaminates. Unless otherwise noted, all test welds which were to be radiographically inspected were mechanically scraped approximately one inch on either side of the fusion area. This cleaning operation was performed immediately prior to welding.

2.4 MECHANICAL TESTING

All mechanical testing was accomplished on a Weideman Mark G, 60,000 pound capacity, screw driven universal test machine. Tensile elongation was measured by means of a deflectometer which translates the mechanical motion of the cross head to an electrical output which, along with load, can be recorded to give an autographic load-elongation curve. The tests were run at a cross head speed of .005 inch/inch/minute through the 0.2 percent offset yield point and then increased to 0.05.

Free bend testing to determine weld ductility was conducted on the same universal test machine. All tests were performed in a manner consistent with the requirements of ASTM E16-57T.

3. TASK C - ESTABLISHMENT OF MAXIMUM WELDABLE THICKNESS

3.1 INTRODUCTION

The basic objective of this program phase was to establish weld parameters for a variety of material thicknesses up to the maximum capability of the NASA 15 KVA welder. Welds were to be produced in these thicknesses using the minimum heat input consistent with ability to meet the radiographic requirements of ABMA-PD-R-27A, Class II.

Previous development had established basic weld settings using the lower power, but similar, 10 KVA laboratory welder. In this work, employing the NASA equipment, the relationship to previous data was established and weld energy speed combinations determined for material thicknesses to 0.832 inch. The maximum weldable thickness was established in the 2219 aluminum and porosity occurrence evaluated for all weld conditions.

Mechanical testing (tensile and free bend) was performed on a series of 12 inch long welds in 1/4 inch thick material produced with conditions which provided consistent X-ray quality on a given weld and from joint to joint.

3.2 RESULTS

Previous development had established weld conditions for joining 2219 aluminum at power levels to 6 KW (5.1 KW transmitted to the work). With proper shielding and pre-cleaning, acceptable welds could be produced under lower speed conditions (and lower power) and at speeds reduced from the bench mark for the higher level power input. In these studies inadequate shielding or pre-weld cleaning had resulted in scattered porosity over the complete range of test conditions. At high speed bench mark conditions, heavy center-line voids had occurred.

Using the gas shield technique developed in this earlier work (see Figure 4) welds were produced with the NASA-15 KVA welder at machine settings which essentially duplicated the earlier tests, thus demonstrating the interchangeability of weld settings from unit to unit. These conditions were as follows:

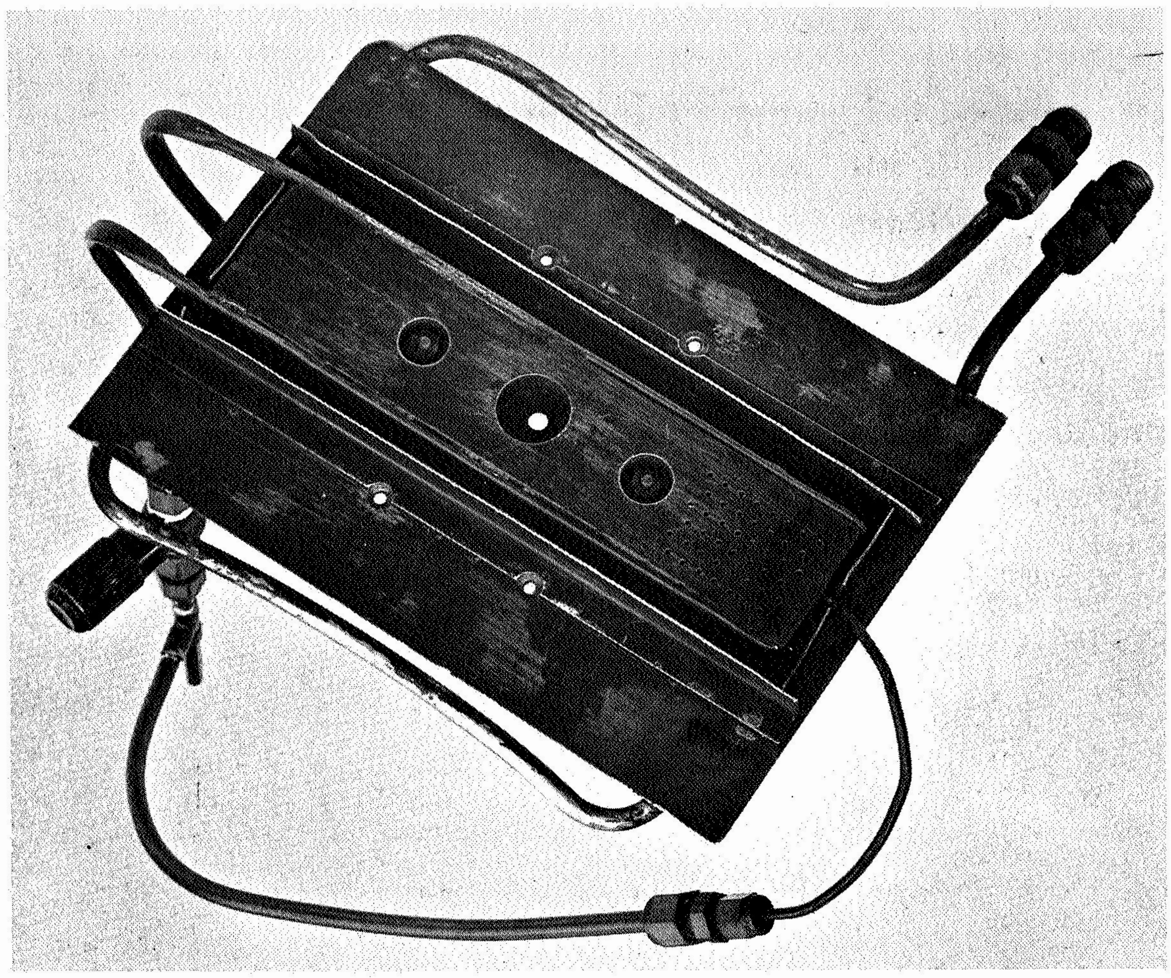


Figure 4. Gas Shield Device for Out-of-Vacuum Electron Beam Welding

Power Input to Gun	Power Transmitted to Work	Work Distance	Bench Mark Weld Speed
3.6 KW	3 KW	9/16 in.	20 IPM
4.25 KW	3.6 KW	9/16 in.	25 IPM
6.0 KW	5.1 KW	9/16 in.	60 IPM

At the bench mark speed for the 6 KW power level, welds consistently meeting the ADMA-PD-R-274, Class II radiographic inspection requirements could not be produced, regardless of shielding and pre-cleaning. At the lower speed bench mark conditions noted, or at speeds less than the bench mark for the 6 KW power level, the radiographic quality was obtained. These results confirmed earlier findings on porosity occurrence.

Parameters producing the lowest total heat input (kilojoules/inch of weld/inch of thickness) to the work piece and which produced the desired weld quality were selected and a series of 12 inch long weld joints were made in the 1/4 inch material. The parameters used were as follows:

Power Input to Gun	Power Transmitted to Work	Work Distance	Weld Speed	Heat Input
6 KW	5.1 KW	9/16 in.	45 IPM	27 KJ/in./in.

A helium gas shield and backup gas were employed. All welds produced with these conditions met the appropriate Class II radiographic inspection requirement without exception. A typical X-ray and weld cross section is shown in Figure 5. These weld panels were cut and tensile and bend specimens removed and identified as shown in Figure 6. The mechanical tests were made with the weld bead present and also with the bead shaved to base metal thickness. The results obtained are listed in Table 1.

The average ultimate strength of the joints in the as-welded condition was 42,500 PSI. Weld build-up that occurred with the selected parameters was a maximum of 0.020 inch total on the face and root. Even this minor amount, however, increased average strength by approximately 2000 PSI. The free bend test also showed an effect of bead removal. The maximum bend angle was lower on the shaved welds.

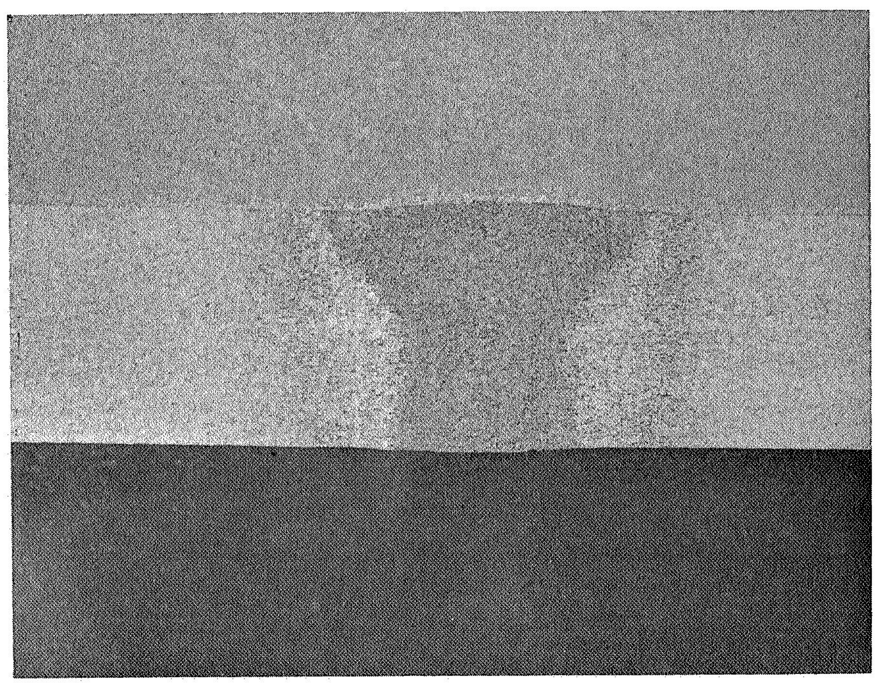
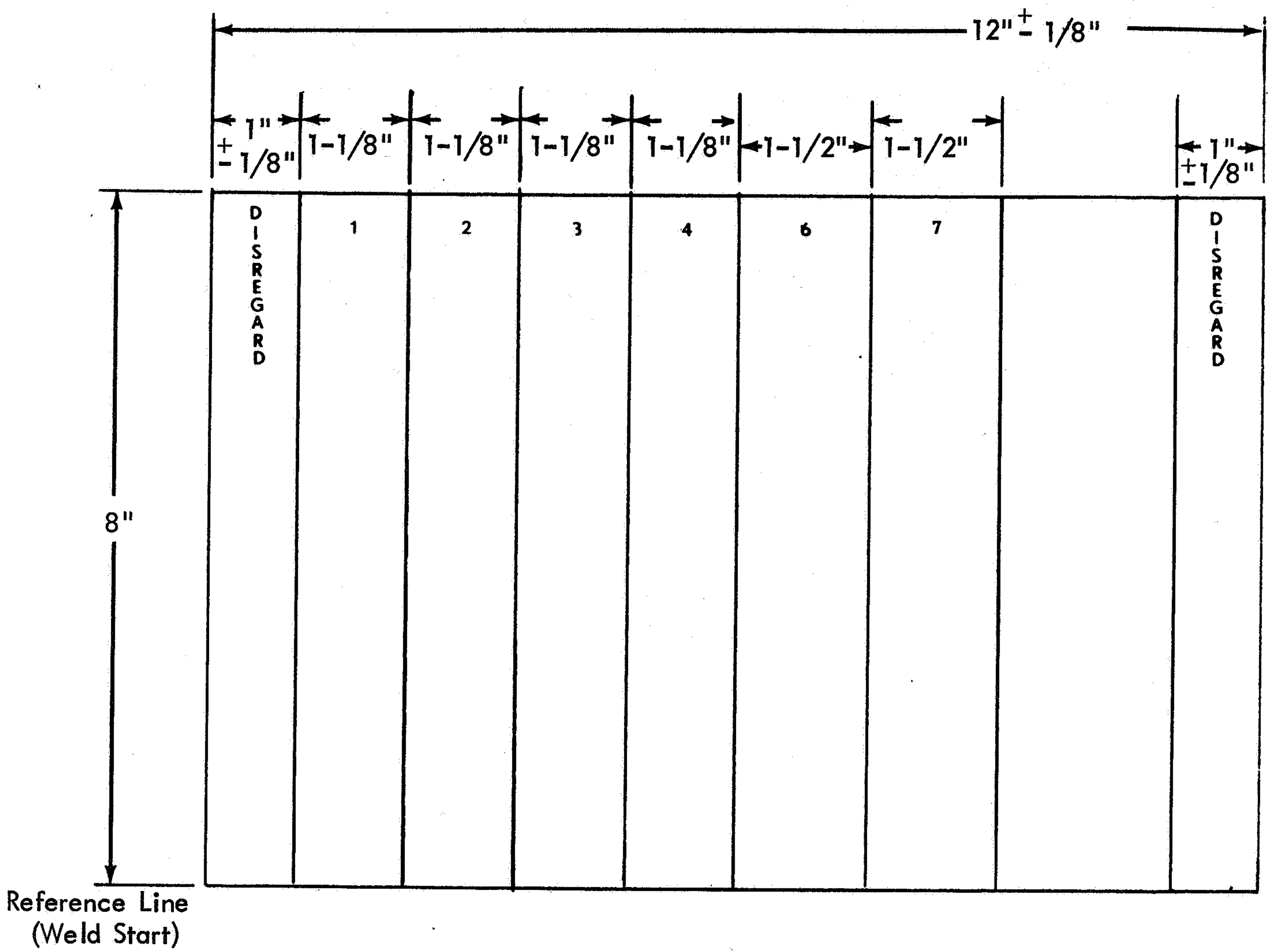


Figure 5. Radiograph and Cross Section of Typical Low-Speed Weld Produced for Mechanical Testing
1/4 inch, 2219-T87 Aluminum
No. 162: 6 KW-I_p, 5.1 KW-I_t, 9/16 D_t, 45 IPM



NOTES:

1. Identify specimens by weld serial number and distance from reference line.
2. Retain identification thru all test preparation.
3. Radiograph per ABMA-PD-R-27A, Class 2.
4. Visually examine per ABMA-PD-W-45. (Disregard 1" on each panel end and upper and lower weld reinforcement)
5. Test specimens to be taken from areas meeting inspection requirements.

Figure 6. Materials .375" Thickness or Less

TABLE 1

TENSILE AND BEND TEST DATA ON 2219 ALUMINUM WELDS

1/4 INCH MATERIAL - ALL WELDS MET CLASS II REQUIREMENTS OF ABMA-PD-R-27A

Tensile Tests

Spec. No.	Ultimate Tensile Strength (psi)	Yield Strength 0.2% Offset (psi)	Elongation % 1/2 in. G. L.	1.0 in. G. L.	2.0 in. G. L.
129.1*	39,900	33,200	16.0	8.0	4.0
129.2*	40,700	33,700	16.0	8.0	4.0
129.3	42,500	34,400	16.0	8.0	4.0
129.4	42,600	35,500	14.0	7.0	3.5
161.1	42,300	35,500	14.0	8.0	4.0
161.2*	40,400	33,400	18.0	8.0	4.0
161.3*	41,700	33,700	8.0	8.0	3.0
161.4	42,000	34,500	16.0	8.0	4.0
162.1	42,300	35,000	14.0	8.0	4.0
162.2	42,500	34,900	18.0	9.0	4.0
162.3*	41,400	39,600	18.0	8.0	4.0
162.4*	41,600	---	16.0	8.0	4.0
166.1*	41,200	39,100	16.0	8.0	4.0
166.2	42,600	34,600	16.0	8.0	4.0
166.3	42,400	35,200	16.0	8.0	4.0
166.4*	40,600	33,900	14.0	7.0	3.5
171.1*	40,000	33,800	14.0	7.0	3.5
171.2	42,700	---	14.0	7.0	3.5
171.3*	40,300	34,200	16.0	8.0	4.0
171.4	42,400	34,600	16.0	8.0	4.0

Bend Tests

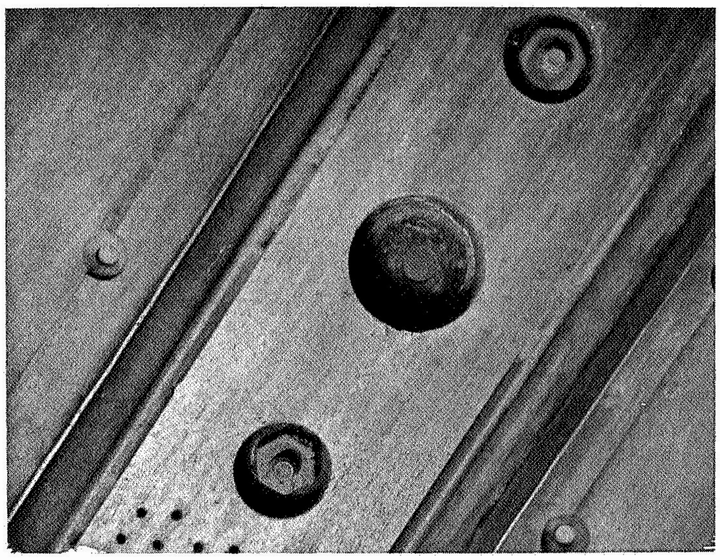
Spec. No.	Peak Load	Bend Angle
161.6	1040	30°
161.7*	850	28°
129.6	1040	32°
129.7*	895	28°
162.6	1075	42°
162.7*	800	22°
166.6	1085	40°
166.7*	885	28°
171.6	1125	45°
171.7*	790	20°

*Weld ground flush with base metal

While extending the experience to welding of heavier material, in order to establish a maximum weldable thickness for the NASA-15 KVA welder, an operational problem became apparent. To extend the basic penetration capability at a given power level, shorter work distances were evaluated. The distance between the work and the gun (D_t) has been recognized as a critical variable and was evaluated in Tasks A and B. These tests (see Technical Progress Summary, February 1966) had demonstrated increasing penetration as the work distance was decreased. On the heavier materials, the combination of the required high power and relatively low weld speed (less than 20 IPM in some cases) cause considerable splatter and vaporization of aluminum. A particularly heavy build-up of this material would collect around the gun orifice after relatively short weld lengths at smaller work distances. This material would periodically fall into the weld, forming a rough contaminated surface and occasionally developing mechanical interference between the gas shield and the work. Figure 7 shows the typical before-and-after condition on the shield after approximately 12 inches of welding.

The problem of metal build-up at the gun orifice was particularly severe at short work distances. This difficulty was not resolved within the scope of this program. At the 9/16 inch D_t used for the final test welding of the heavy plates (0.712 and 0.812) the problem was less severe and did not prevent the production of required test welds with lengths up to 12 inches.

To determine the maximum weldable thickness capability for the NASA welder, joints were produced in 0.500 inch, 0.712 inch and 0.832 inch thick 2219 aluminum. The highest speed at which these plates could be penetrated was evaluated. In addition lower speed was of interest since the work with thinner material had suggested that lower speeds were necessary to achieve desired porosity level. The heavy plate welding demonstrated that the lowest practical speed on any material thickness must be related to the ability to control penetration. The difference in weld speed between a lack of penetration and an excess penetration weld became extremely small as lower power levels (and thus reduced speeds) were employed. This difference also became much narrower as material thickness increased.



BEFORE

AFTER

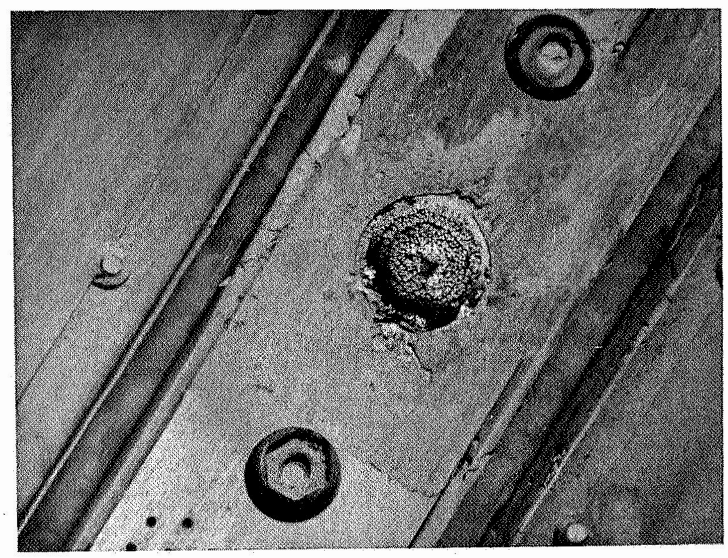


Figure 7. Shield Build-Up During a High Power Low Speed Weld 12-inch Weld at 8.25 KW, 8 IPM, 2219 Aluminum - 0.712-inch Thickness

Thus, the establishment of maximum weldable thickness for a given available power must actually have as a prime consideration the ability to control penetration over a practical range of variables in addition to the basic ability to fuse through a given material thickness. Weld tests on the 0.832 plate stock evaluated in this work demonstrated that variation of speed from 10 to 12 IPM, at full machine power of 12 KW, resulted in very wide changes in penetration. The following table shows typical weld data on this material:

Typical Weld Parameters for 0.832 inch-2219-T87 Aluminum

Weld	Power Input To Gun KW	Power Transmitted To Work KW	Voltage KV	Speed IPM	D_t Inches	Heat Input To Work KJ/in./in.	Results
122	12	10.5	150	12	9/16	63	Intermittent Penetration
123	12	10.5	150	12	9/16	63	Lack of Penetration
124	12	10.5	150	11	9/16	69	Inconsistent Penetration
130	12	10.5	150	11	9/16	69	Uniform Penetration
131	12	10.5	150	11	9/16	69	Uniform Penetration
120	12	10.5	150	10	9/16	76	Excess Fall Through and Cracking
132	12	10.5	150	10	9/16	76	Heavy Globular Fall Through

Duplication of weld results under these widely varying penetration conditions was extremely difficult. At lower power levels than those listed, welding was not feasible. Figure 8 is a cross section of a weld made with the most satisfactory settings, 12 KW and 11 IPM.

In the joining of 0.712 inch material a wider tolerance for parameters was available as shown in the table below. Welds were more uniform in penetration over a broader range of conditions than those in the heavier plate. Closer reproduction from sample to sample at the same conditions was also observed. From this work it appears that the 0.712 inch 2219 Al is a realistic approximate thickness limitation in order to provide sufficient process latitude for the widest range of applications.

Typical Weld Parameters for 0.712 inch 2219-T87 Aluminum

	Weld Lower To Gun KW	Transmitted Lower KW	Voltage KV	Speed IPM	Gun to Work Distance Inches	Heat Input to Work KJ/in./in.	Results
138	12	10.8	150	15	9/16	60.7	Excess Penetration - Cracking
137	12	10.7	150	14	9/16	60.2	Excess Penetration - Cracking
119	12	10.2	150	15	9/16	57.3	Satisfactory Penetration
140	12	10.7	150	17	9/16	53	Satisfactory Penetration
141	12	10.7	150	17	9/16	53	Satisfactory Penetration
142	12	10.5	150	17	9/16	52	Satisfactory Penetration
139	12	10.7	150	18	9/16	50	Intermittent Penetration
118	12	10.3	150	18	9/16	48.5	Intermittent Penetration
145	10	8.55	150	10	9/16	72	Excess Penetration - Cracking
146	9.5	7.95	150	10	9/16	67	Satisfactory Penetration
147	9.5	7.95	150	10	9/16	67	Satisfactory Penetration
144	9	7.5	150	10	9/16	63	Intermittent Penetration
143	8	6.45	150	10	9/16	54.3	No Penetration
158	8	7.05	150	8	9/16	74.2	Satisfactory Penetration
157	7.5	6.6	150	8	9/16	69.5	No Penetration

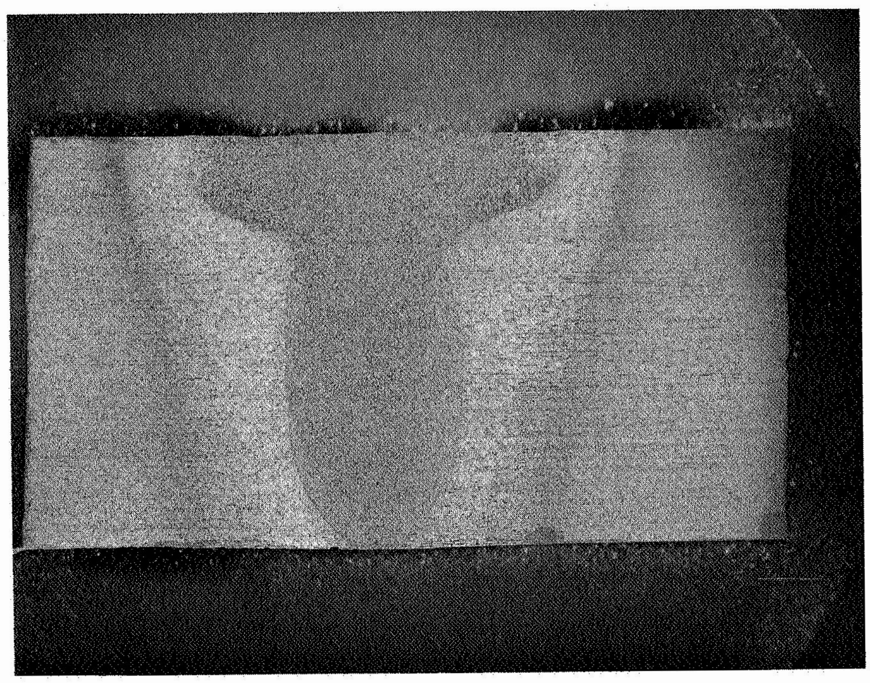


Figure 8. Out-of-Vacuum Electron Beam Weld in 0.832 inch, 2219-T87 Aluminum No. 131: 12 KW-I_p, 10.5 KW-I_t, 9/16 D_t, 11 IPM

Figures 9 and 10 show cross sections of the high and low speed welds in this material thickness.

Radiographic inspection of the heavy plate welding described showed heavy porosity even at the lowest speeds that could be used. Improvement with decreasing speed was evident, however. Welding of 0.500 plate provided enough tolerance to changing parameters that the porosity occurrence could be more carefully investigated for this intermediate thickness.

Welding of the 1/2 inch plate was conducted over a wide range of conditions. Bench mark speeds were established for power levels from 5.5 to 12 KW. A listing of a number of these bench mark conditions is shown in the following table.

Bench Mark Weld Conditions for 1/2 inch 2214-T87 Plate

Weld No.	Weld Power To Gun (KW)	Transmitted Power (KW)	Voltage (KV)	Work Distance (Inches)	Bench Mark Speed (IPM)
99	12	10.9	150	9/16	45
105	11.7	10.5	150	9/16	42
94	8.5	7.8	150	9/16	25
76	8.5	7.5	150	1/4	25
107	8	7.1	150	9/16	20
108	6.5	5.9	150	9/16	15
111	5.5	5.1	150	9/16	14

Figures 11 and 12 are cross sections showing general weld configuration for the higher and lower speed weld conditions listed.

As in previously discussed work on the various material thicknesses, the porosity level was reduced by reduction in speed. However, even at the minimum practical bench mark speed (5.1 KW, 14 IPM), the welds would not meet the Class II radiographic requirement. At slightly higher speed bench mark conditions (20 IPM) porosity became severe.

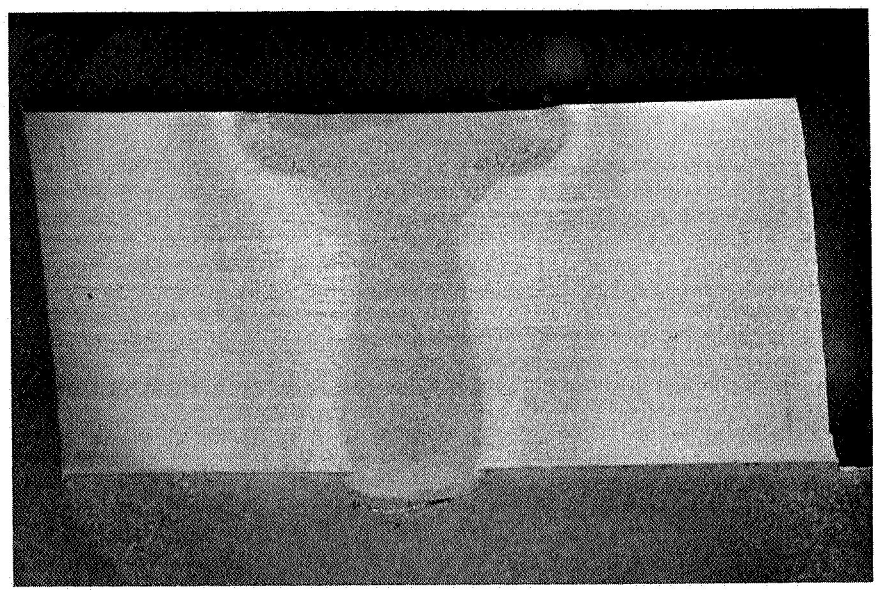


Figure 9. Out-of-Vacuum Electron Beam Weld in 0.712 inch, 2219-T87 Aluminum
No. 141: 12 KW-I_p, 10.5 KW-I_t, 9/16 D_t, 16 IPM

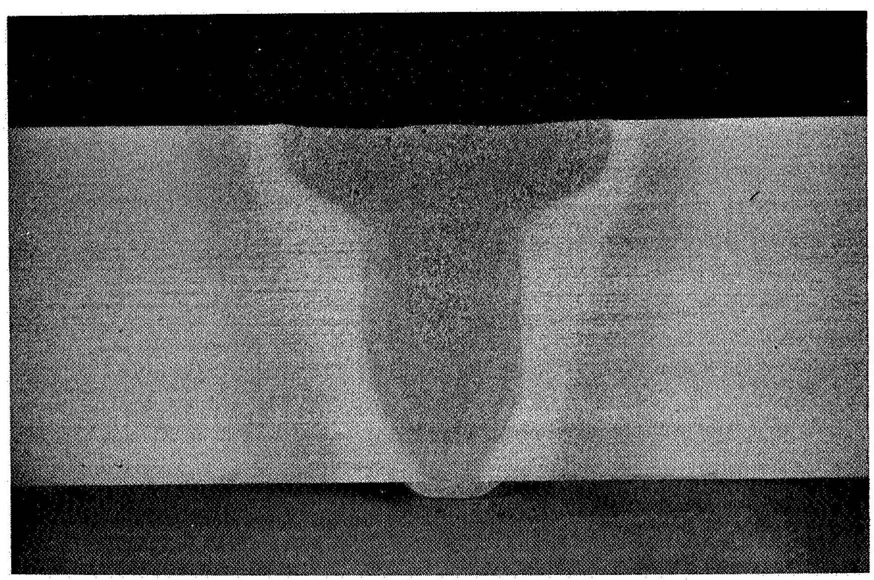


Figure 10. Out-of-Vacuum Electron Beam Weld in 0.712 inch, 2219-T87 Aluminum
No. 158: 8 KW-I_p, 7 KW-I_t, 9/16 D_t, 8 IPM

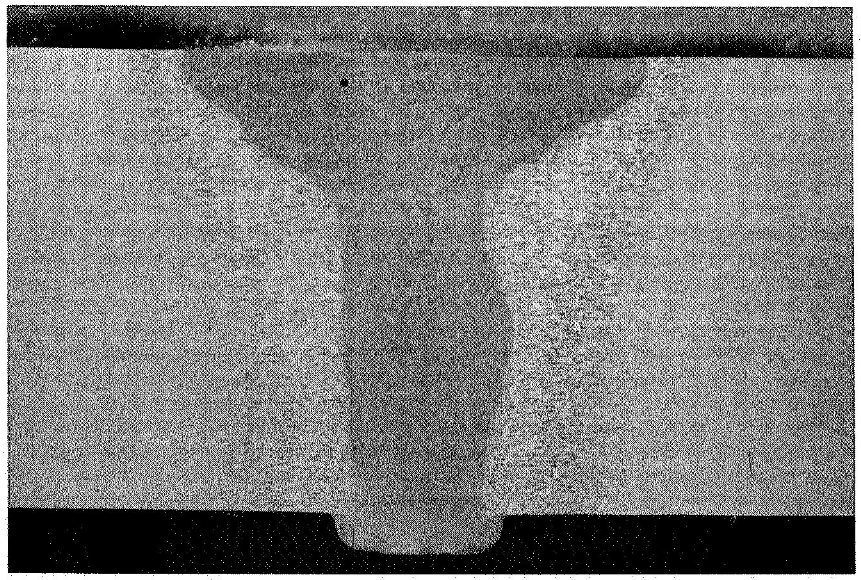


Figure 11. Out-of-Vacuum Electron Beam Weld in 0.500 inch, 2219-T87 Aluminum
No. 105: 12 KW-I_p, 10.5 KW-I_t, 9/16 D_t, 45 IPM

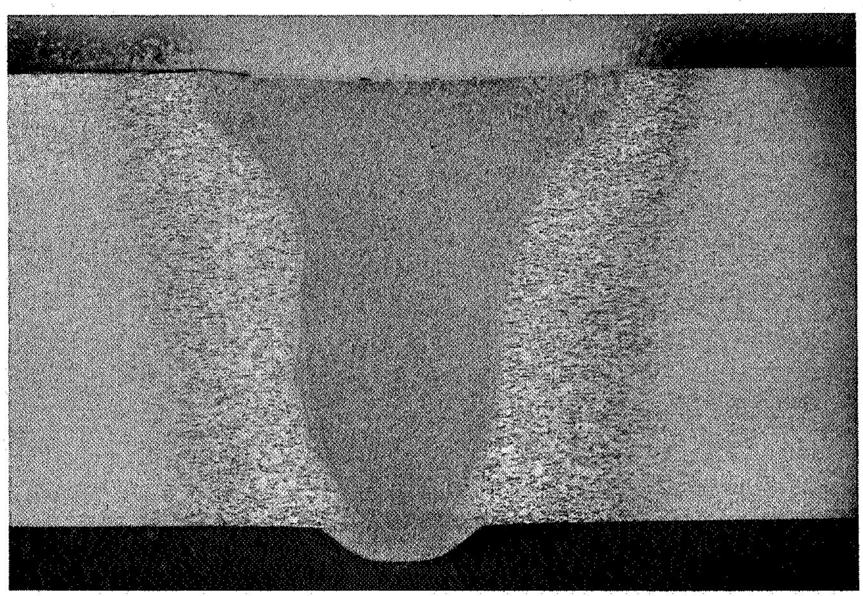


Figure 12. Out-of-Vacuum Electron Beam Weld in 0.500 inch, 2219-T87 Aluminum
No. 111: 5.5 KW-I_p, 5 KW-I_t, 9/16 D_t, 14 IPM

Reduction in speed below the bench mark for a given weld energy level was effective in reducing porosity only for lower power levels. Figure 13 shows a weld which approached the radiographic quality desired. This weld was produced at 5.1 KW input power and 12 IPM.

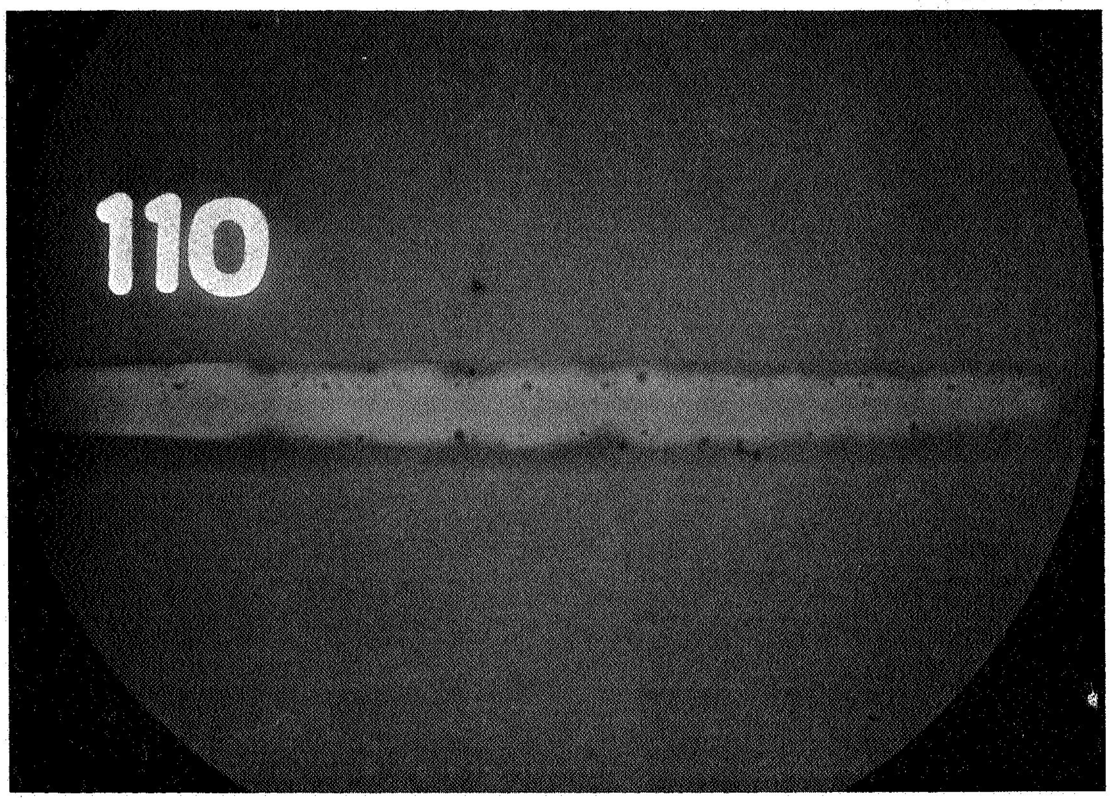


Figure 13. Out -of-Vacuum Electron Beam Weld in .500 in., 2219-T87 Aluminum, No. 110: 5.5KW-I_p, 5 KW- I_t, 9/16 in. D_t, 12 IPM

4. TASK D - PRODUCTION OF NARROW-LOW ENERGY INPUT WELDS TO DEVELOP INCREASED STRENGTH

4.1 INTRODUCTION

The application of the NASA-15KVA Out-of-Vacuum electron beam equipment to the welding development study permitted the exploration of a welding power spectrum much broader than previously available. This unit, operating at its maximum rated output, delivers approximately 10.5 KW to the work piece. Previous extensive studies had been limited to 5 - 6 KW transmitted power level. The greater available power may be applied to joining of thicker material, as has been discussed in Task C, or to higher speed welding of the thinner material as studied in this task.

The studies at the lower weld energies conducted as Tasks A and B had provided empirical indications on 1/4-inch 2219 aluminum that much higher weld speeds, more favorable depth to width ratios, and reduced energy input (KJ/in/in) would be possible at higher power. The welding conducted under Task D used this higher power and actually developed the parametric relationships that exist and determined the improvements in weld aspect ratio and tensile strengths which occur.

Furthermore, independent work performed by Westinghouse had demonstrated the critical importance of gas flow from the gun on weld configuration. This new variable, and the effects, was introduced into the program and explored over a wide range of weld conditions.

4.2 RESULTS AND DISCUSSION

4.2.1 Weld Power and Work Distance Effects

The parameters to be explored in establishing the weld conditions for high power operation were:

Input Power to Gun	3.6 to 12 KW
Transmitted Power Level	~3 to 10.5 KW
Gun to Work Distance	1/8 in. to 9/16 in.
Weld Speed	Bench mark for various power levels
Gas Flow to Gun	100 - 160 CFH

Limits on operational power levels were established by the basic capability of the welder. The work distance limitations were determined on the minimum side by the occurrence of mechanical interference between the gun and the work piece. The maximum work distance was selected as that level beyond which beam spread becomes a critical factor. The protective gas flow into the out-of-vacuum electron beam welder is actually only an indirect measurement of the gas coming from the bottom plate of the welder. This effluent flow at a given input value is related to, and affected by, a number of operating conditions. The size and shape of the hole in the bottom gas protective shield, the size of the lower orifices, and metal deposits in the gas flow areas all have a considerable effect. The input flow limits noted were established as the points at which no exit gas was apparent (low side) and at which excessive turbulent flow occurred.

In the first series of tests at short work distance (down to 1/8 in.), it became apparent that metal deposits were getting past the gas shield plate and forming a build-up on the bottom gun orifice. These deposits altered gas flow sufficiently to cause great difficulty in repeatability of weld penetration data. The bottom shield of the gun had been used for a considerable length of time and the center hole had been eroded to a somewhat larger size. This part was modified to incorporate a replaceable center section, made from copper, with the proper hole diameter. The repair provided the proper protection for the lower gas orifices and thus improved reproducibility of weld results.

With the achievement of more reproducible conditions as a result of the improved bottom shield, a complete series of weld parameters was developed for 1/4-inch 2219 aluminum at power levels up to the maximum available transmitted power level of 10.5 KW.

The early weld results confirmed the importance of control over gas flow, particularly at short work distances. Gas flow into the gun for this series of tests was adjusted to achieve maximum penetration, without excess surface disturbance, at each work distance involved.

Figure 14 is a plot of the data obtained. Also shown is a background plot of calculated heat input values. It can be seen that in all cases, as welding energy and the speed associated with bench mark type penetration are increased, the process becomes more efficient, i.e., heat input is reduced. The lowest heat input level achieved in this test group was 10.5 KJ/in/in.

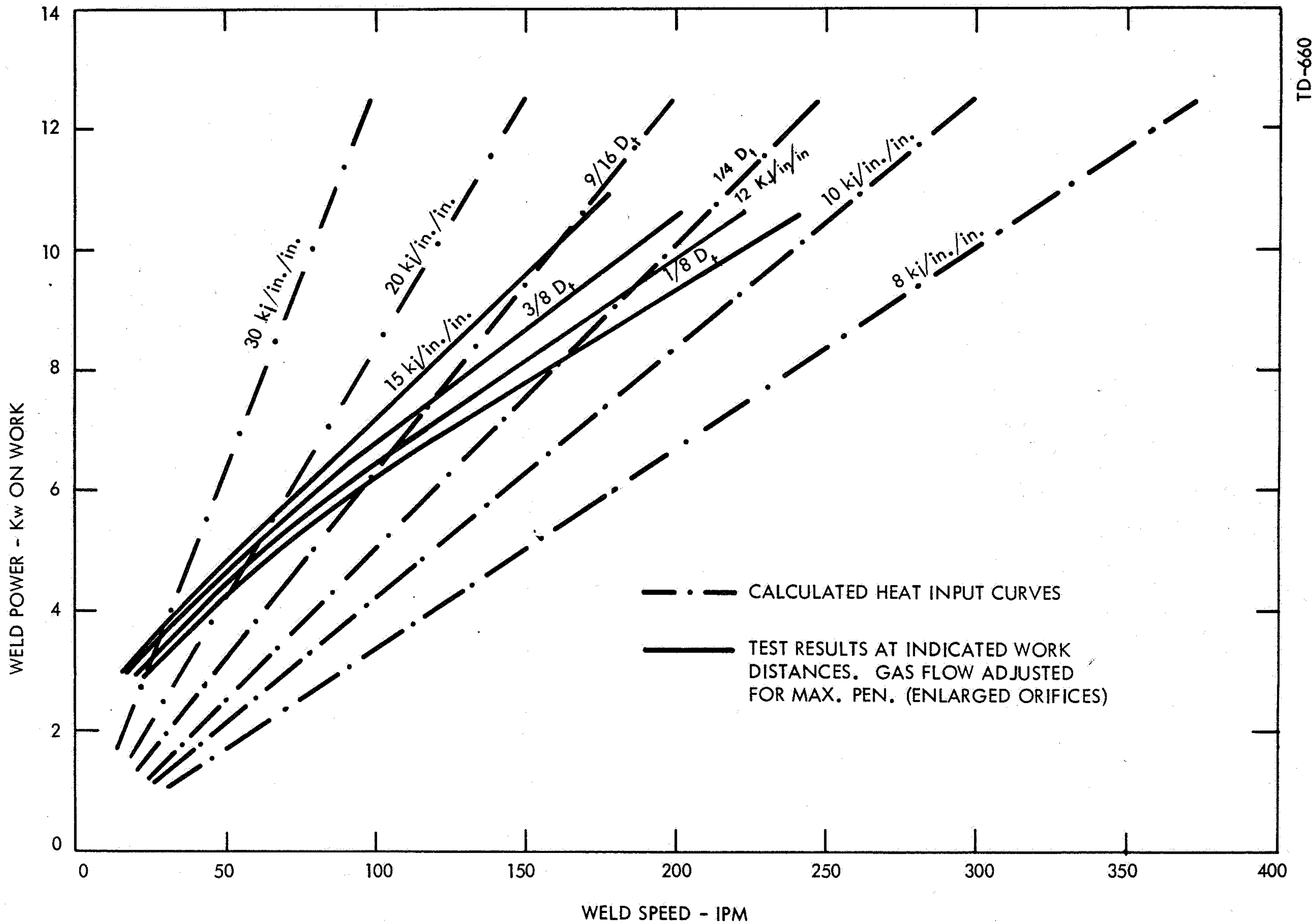


Figure 14. Weld Parameters Related to Heat Input-Bench Mark Penetration, 1/4 in. Material

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This value compares favorably with reported values for in-vacuum processes.

Decreasing work distance has the effect of reducing weld width and increasing the speed at which a weld would be produced using a given power level. In these tests, the increase in speed was essentially linear as indicated by Figure 15. The effect was also more significant at the higher power levels. As noted previously, the minimum gun to work distance that could be evaluated on 1/4-inch material was 1/8 inch due to interference with work travel.

Further analysis of the weld series was conducted by cross sectioning to evaluate fusion zone configuration. Weld shape and size were determined and related to work distance and weld power as shown in Figure 16. It can be seen that weld width decreases rapidly as work distance is decreased (power held constant and speed modified to maintain bench mark type penetration). The relationships are approximately linear, particularly at the higher power levels of prime interest, down to the minimum 1/8-inch work distance.

4.2.2 Improved Gas Flow Conditions

Upon completion of the weld tests discussed above, the pressure within the gun during operation had risen to a point at which it was felt that some maintenance was required. Replacement of flexible vacuum hoses and general checkout of the system yielded only marginal improvement. The lower two gas orifices in the gun, which were original equipment, were inspected and found to have become enlarged approximately 10 percent on the diameter. These orifices were replaced and, during subsequent operation, the pressures within the system returned to levels observed when the unit was new.

Additional welding with the improved system showed that gas flow into the gun had to be reduced from the level used in the recently completed tests to achieve duplication of other weld parameters. This was apparently related to the fact that the smaller orifices that were installed limited the gas flow back to the gun. Thus, at a similar gas flow level into the gun end, a greater amount of effluent flow would occur. This is a basic feature of the gun design, but was, after orifice replacement, restored to a degree not achieved in the immediately preceding test period.

A decision was made to repeat experiments involving variations in gas flow with the new orifices. These experiments revealed that a different weld phenomenon, which resulted

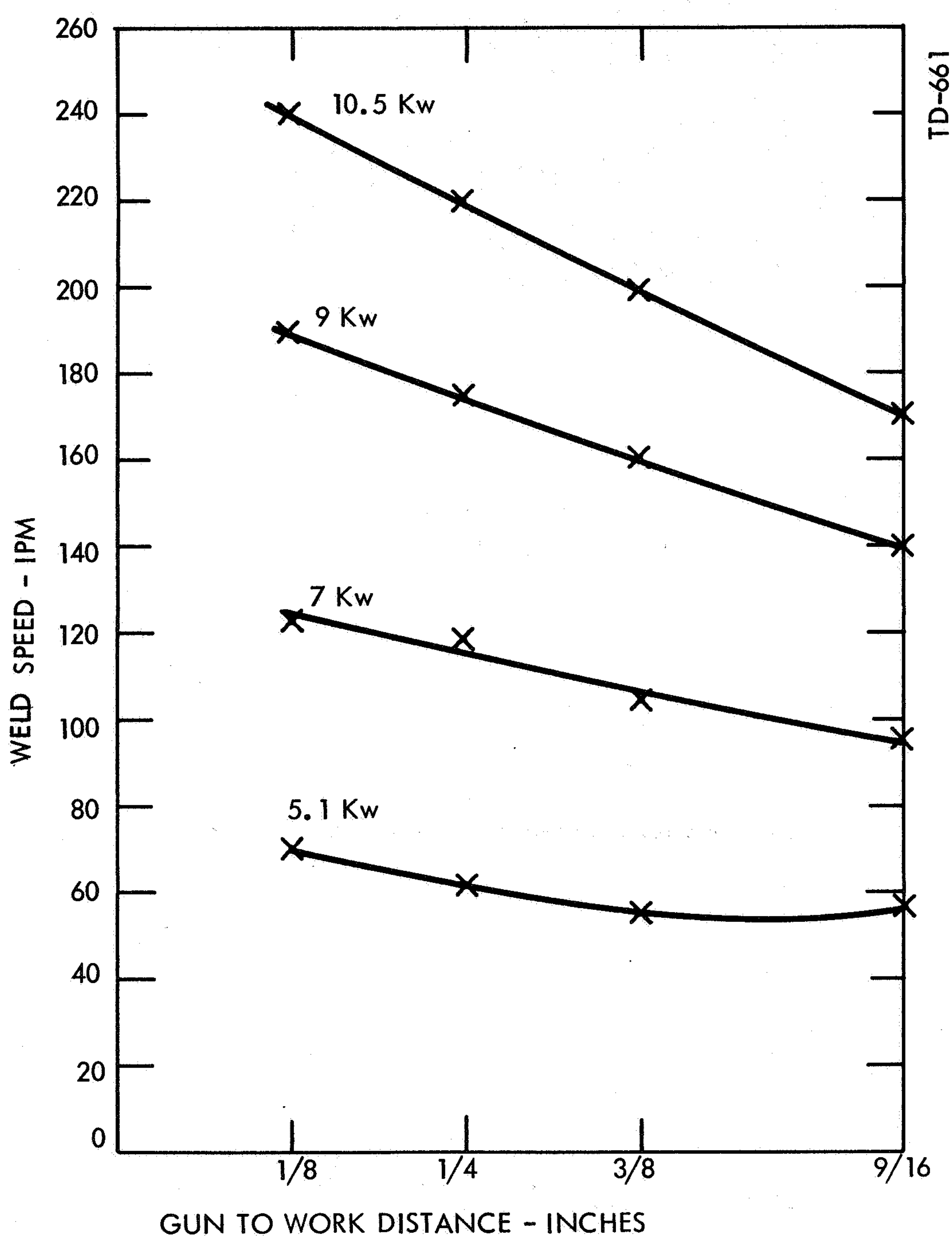


Figure 15. Effect of Work Distance on Weld Speed for Bench Mark Penetration, 1/4 in. Material

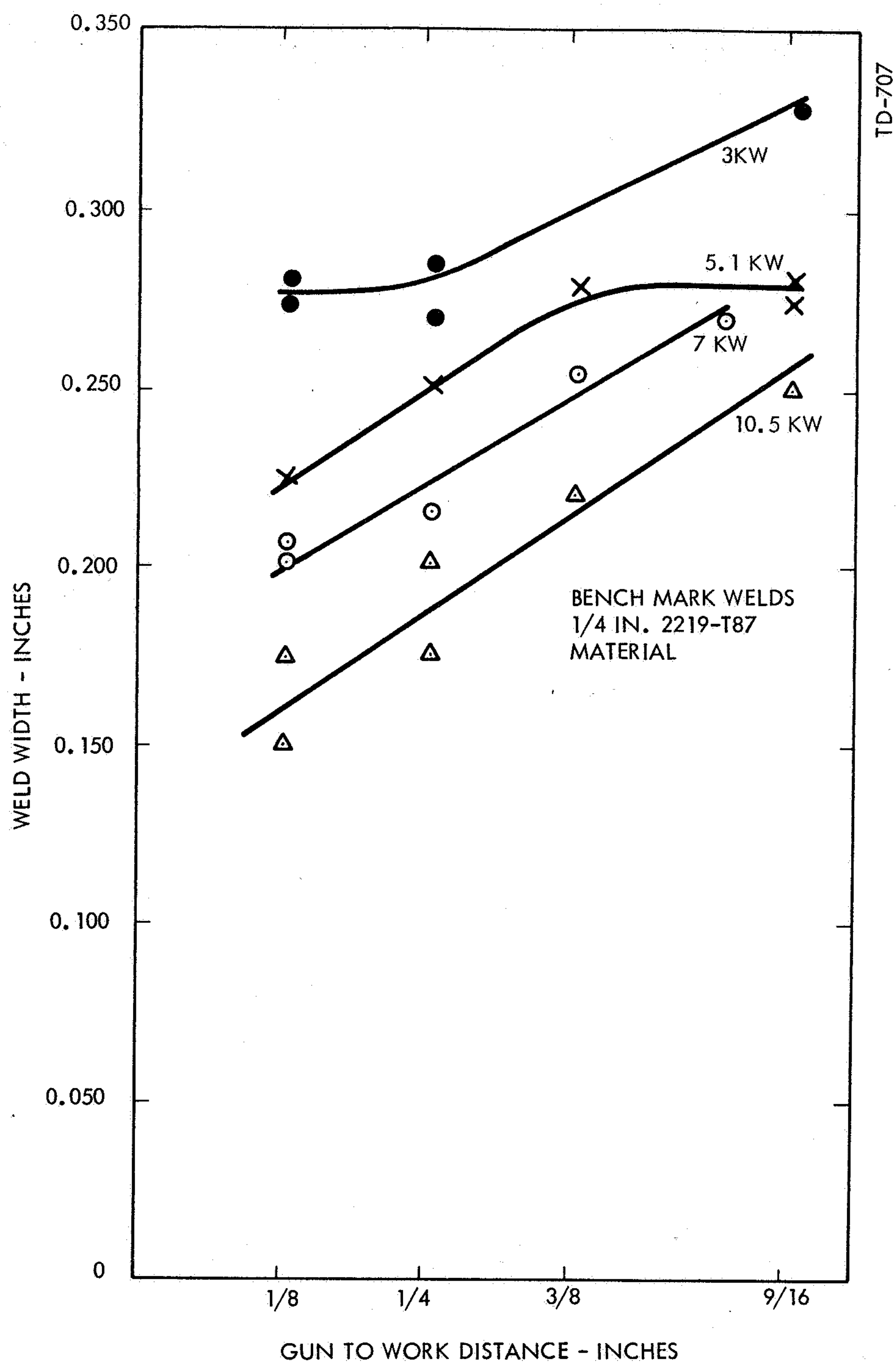


Figure 16 Weld Width Related to Work Distance and Input Power To Work

in significant change in weld width and penetration, could be produced at higher effluent gas flows than previously effective (due to surface disturbance). Appreciably narrower welds were produced at 1/8-inch and 1/4-inch gun-to-work distances than previously obtained. Further, the energy input levels (KJ/in/in) decreased since greater penetration was obtained with similar power input. Figure 17 compares the speed-weld energy relationships established using the apparently more efficient process with those of welds produced in the preceding work. The minimum heat input that was achieved was 8.5 KJ/in/in at the 1/8 inch D_t (reduced from 10.5 KJ/in/in).

Tests conducted with the higher effluent gas flows and the 9/16-inch gun to work distance show little effect on weld width up to the point at which heavy surface disturbance occurred. However, contrary to the effect observed at the short gun to work distance, in this case the high gas flow actually reduced penetration (or the weld speed at which full penetration was achieved). These data may also be seen in Figure 17. Cross sections of welds produced with what has been called the narrow bead phenomena are shown in Figures 18, 19, 20, and 21. Typical weld depth to width relationships observed in these welds were as follows:

Weld Power To Work (KW)	Weld Speed (IPM)	Width (Inches)	Depth/Width Ratio
5.1	70	0.150	1.67
7	140	0.135	1.85
9.75	280	0.100	2.5
10	240	0.110	2.27

A gun to work distance of 1/4 inch was the maximum at which the weld narrowing could be achieved by gas flow adjustment. Welds produced at this point were very similar in appearance to those produced at 1/8-inch work distance as shown in Figure 22.

As will be discussed in the Task E section of this report, whenever the narrow bead phenomena was achieved on the 1/4-inch plate material, very low porosity levels were a corresponding effect. Thus, quality high speed and low energy input welds could be produced for tensile evaluation. In making these longer joints, it was found that duplication of weld

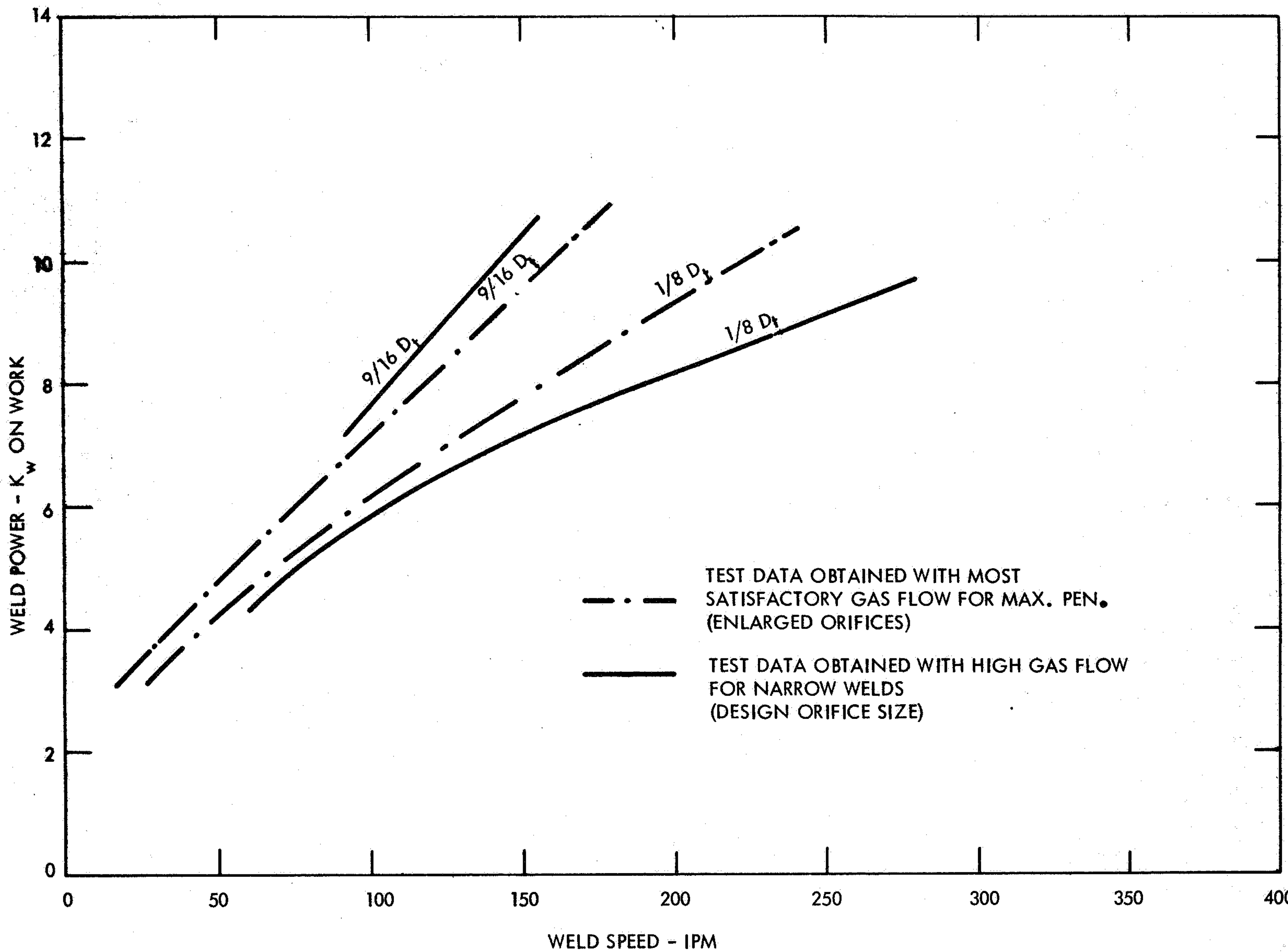
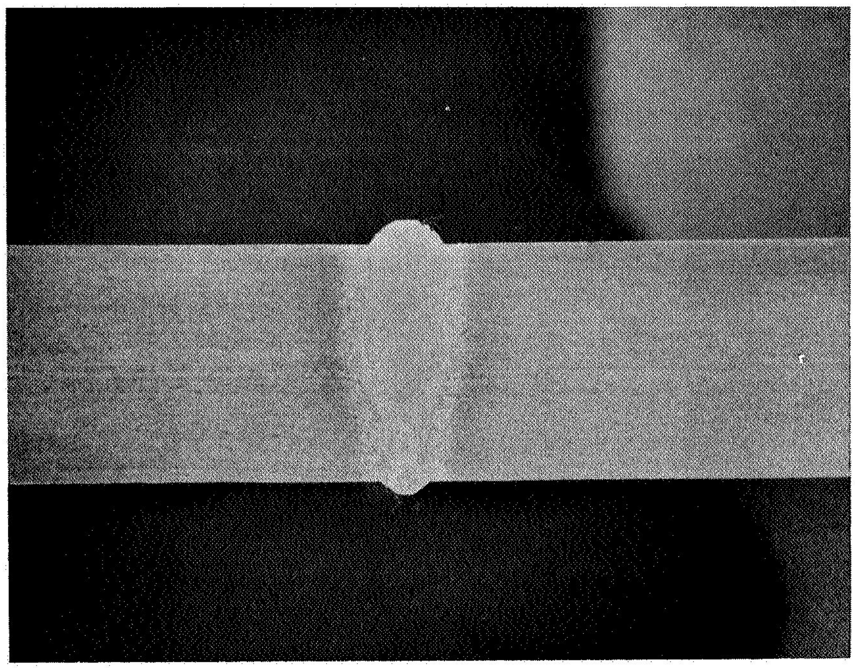


Figure 17. Effect of Gas Flow on Weld Parameters, Energy, Speed Combination for Bench Mark Penetration, 1/4 in. Material



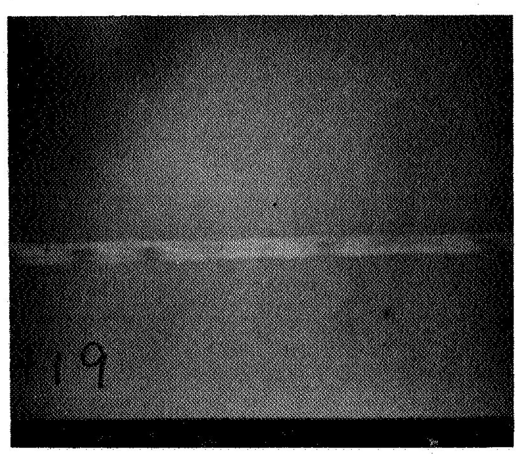
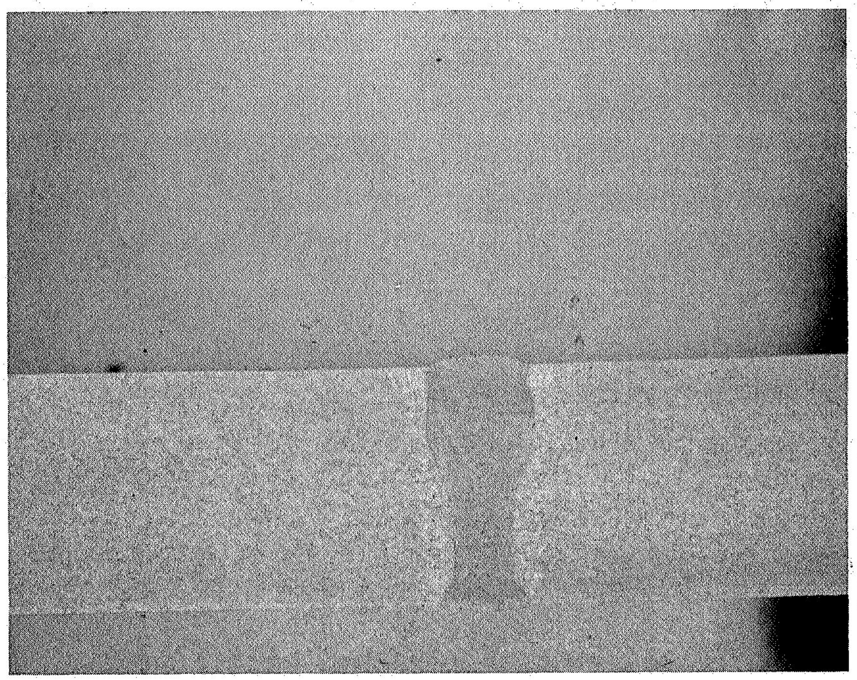


Figure 18. Weld Cross Section and X-ray Photograph of Weld No. 419, (9.75 KW, 280 IPM, 1/8 in. Gun-to-Work Distance) 1/4 in. 2219-T87 Aluminum



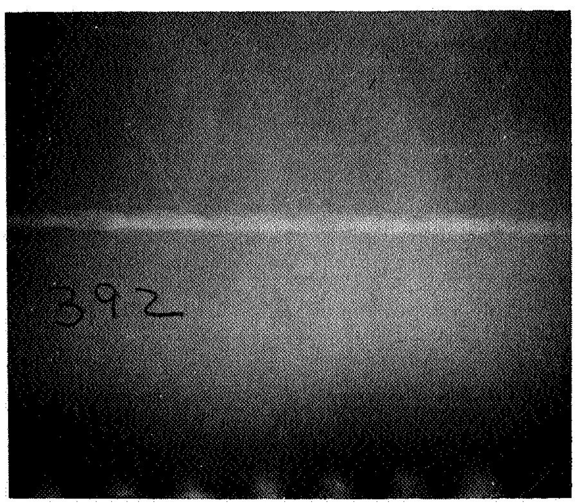


Figure 19. Weld Cross Section and X-ray Photograph of Weld No. 392, (10.5 KW, 240 IPM, 1/8 in. Gun-to-Work Distance)

1/4 in. 2219-T87 Aluminum

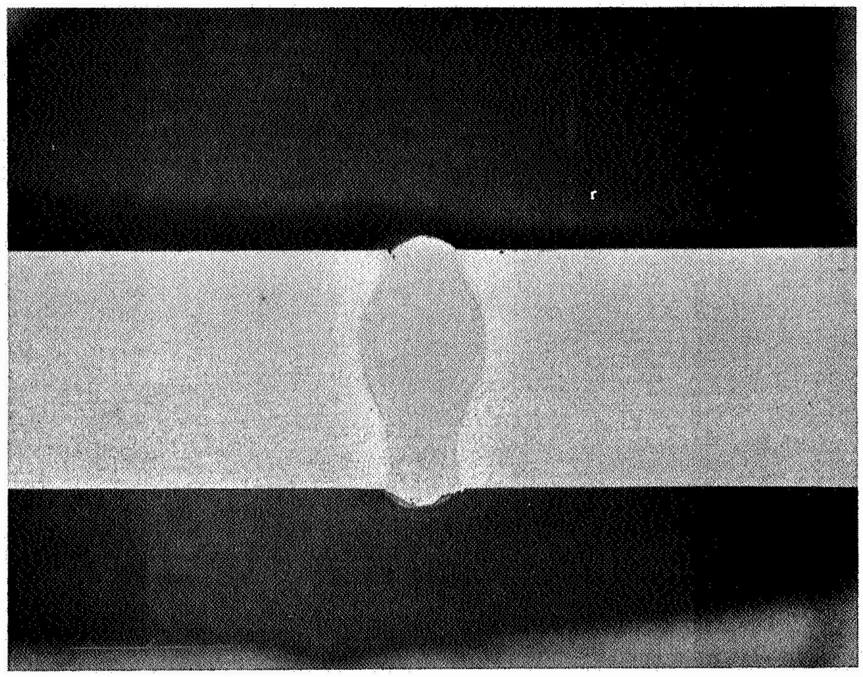
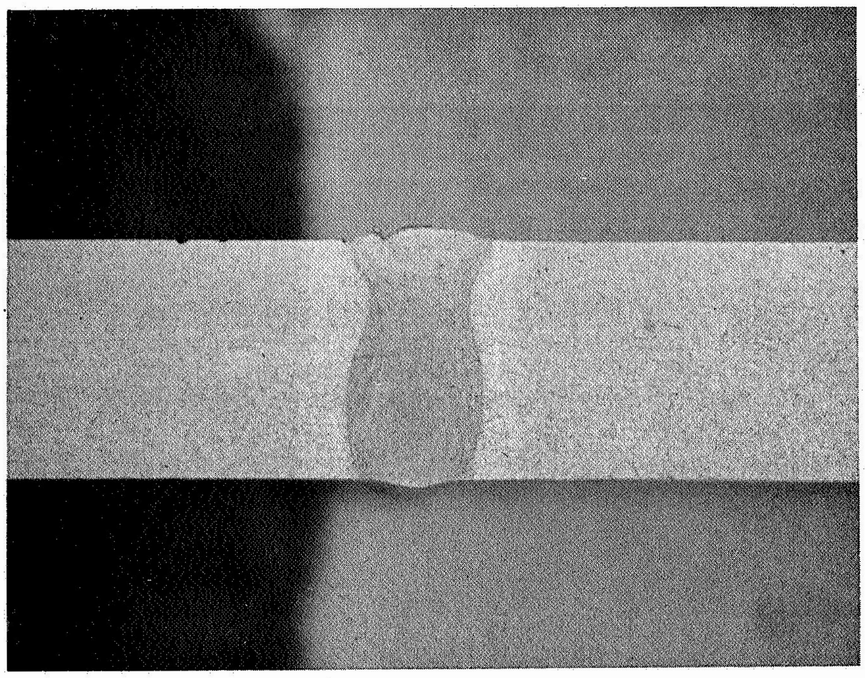


Figure 20. Weld Cross Section and X-ray Photograph of Weld No. 374,
(7KW, 140 IPM, 1/8 in. Gun-to-Work Distance)
1/4 in. 2219-T87 Aluminum



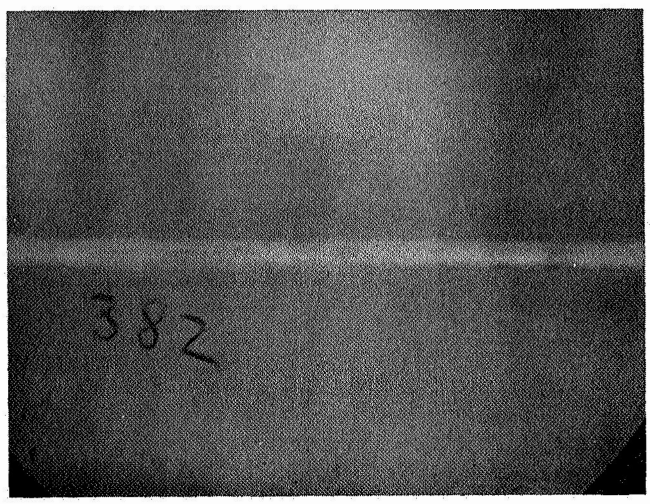


Figure 21. Weld Cross Section and X-ray Photograph of Weld No. 382, (5.1 KW, 70 IPM, 1/8 in. Gun-to-Work Distance) 1/4 in. 2219-T87 Aluminum

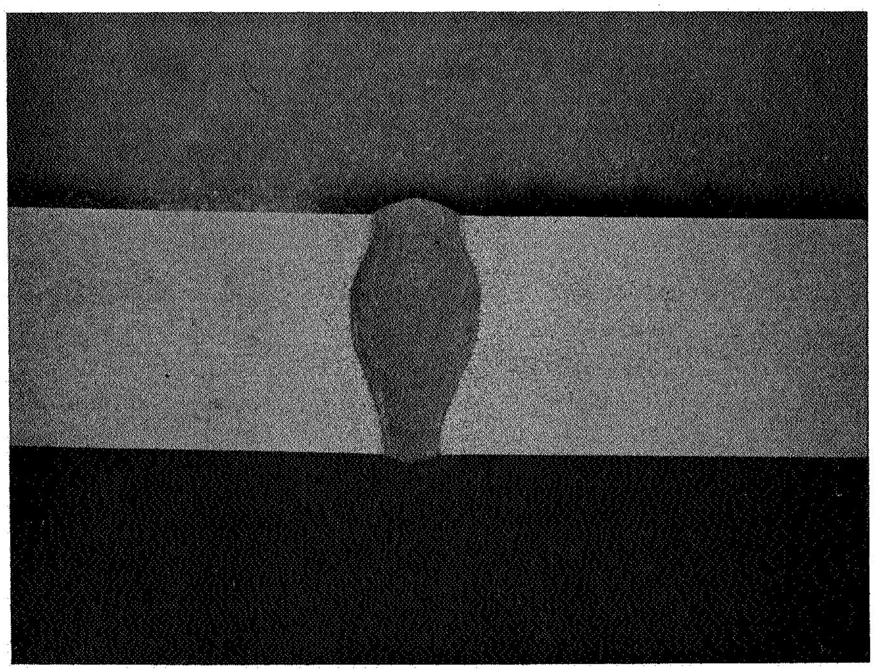


Figure 22. Cross Section of Weld No. 473
(7KW, 140 IPM, 1/4 in. Gun-to-Work Distance)
1/4 in. 2219-T87 Aluminum

appearance could be achieved. However, parameter variation and sensitivity to gas flow adjustment made it necessary to re-establish weld conditions immediately prior to making an actual joint. Further, even short weld lengths (6 to 12 inches) showed inconsistencies from end-to-end.

A number of welds for tensile testing were produced at various levels of heat input. Tensile data for these joints is shown in Table 2. Two factors are of prime significance. First, a number of the weld specimens showed the high strength (47,000 - 49,000 psi) expected based on the low heat input involved. Second, a wide range of strengths were evident between welds made at similar heat input values and also in samples on the same weld. This strength variation is attributed to the contour of the weld face. When welding with the narrow beam phenomena, the weld surface often contains ripples, some of which are below the original surface, causing a notch. The weld cross section shown in Figure 23 illustrates this point. The figure shows the undercut effect and grain orientation of weld number 504. This weld had low test values apparently related to premature failure. Weld number 508 is shown in Figure 24. This weld was produced at similar conditions and heat input levels but had higher measured tensile strength. This weld had a more satisfactory surface without the weld edge effects.

4.2.3 Narrow Bead Phenomena on Heavier Material

Test welding was conducted on 3/8-inch and 1/2-inch plate to determine if the narrow bead, low heat input welding could be achieved on these heavier materials. It was found that the phenomena could be developed but that control was more critical than on the 1/4-inch material previously tested.

The 3/8-inch plate was welded at 10.3 KJ/in/in heat input at 9KW, 140 IPM but surface nonuniformity (variations from the typical wide weld face to a narrow, undercut surface) would occur on a given joint. Radiographic inspection indicated that where the narrow weld bead could be maintained, porosity was not present. However, when weld surface varied and widened, heavy porosity would be formed.

Narrowing of the weld face could also be achieved on 1/2-inch material, but only in a very irregular manner. Comments on surface variation and porosity occurrence on 3/8-inch material also apply to this heavier thickness. Heat input levels required to achieve penetration were similar in these 1/2-inch test welds to those required to produce standard "nail-head"

TABLE 2

AS-WELDED TENSILE STRENGTH OF 1/4 IN. 2219-T87 ALUMINUM WELDED BY THE OUT-OF-VACUUM ELECTRIC BEAM PROCESS

Weld No.	Weld Energy (KW)	Speed IPM	Heat Input (kj/in./in.)	UTS PSI	0.2% YS PSI	% Elongation 1 In.	2 In.
420-1	9.75	280	8.35	42,900	---	5	2.5
-2				47,700	46,900	4	2
421-1	9.75	280	8.35	41,000	---	4	2
-2				40,300	---	4	2
504-1	9.75	280	8.35	41,700	39,800	---	1.5
-2				37,700	---	---	1.5
508-1	9.75	280	8.35	49,200	40,500	---	1
-2				47,500	40,600	---	1
465-1	6.3	140	10.8	45,080	40,850	---	3
-2				48,610	39,120	---	2.5
467-1	6.3	140	10.8	47,190	41,570	---	2.5
-2				46,950	40,920	---	3
-3				44,160	40,960	---	2.5
470-1	7	140	12	45,720	41,090	---	2.5
-2				40,190	40,110	---	1.5

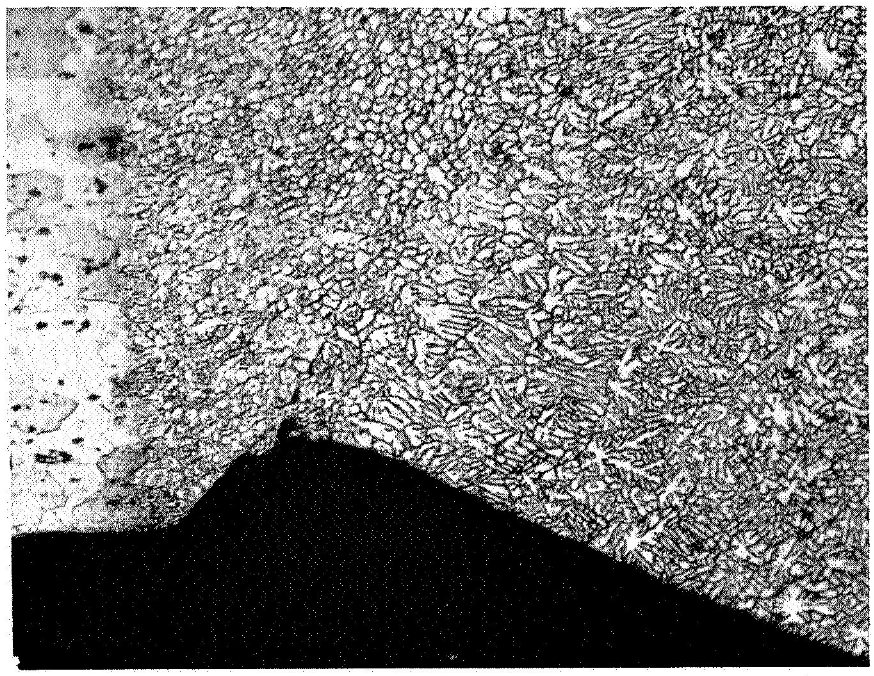


Figure 23. Weld No. 504 - 9.75 KW, 280 IPM,
Low Tensile Strength (39,700 PSI)

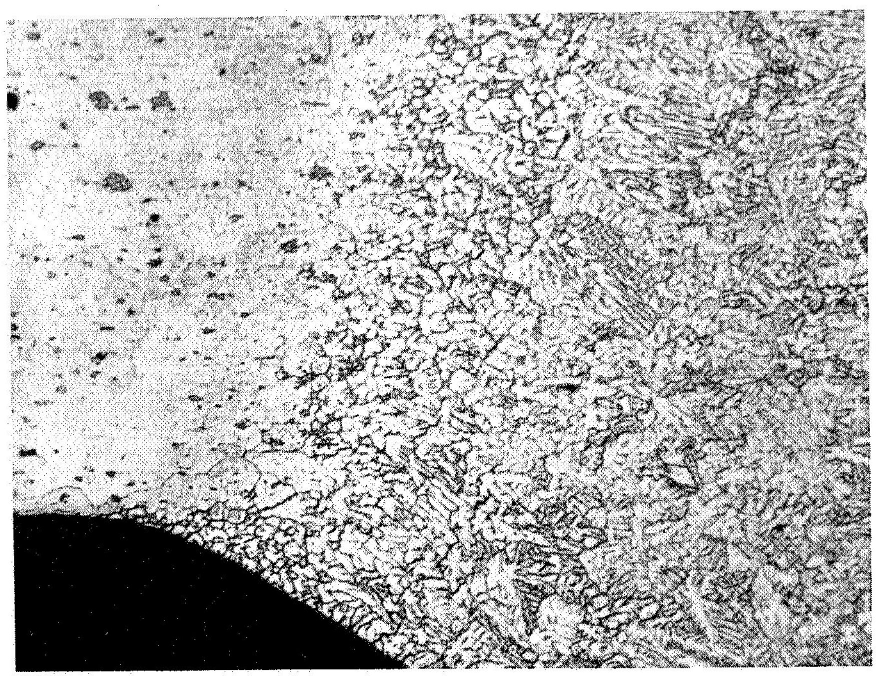


Figure 24. Weld No. 508 - 9.75 KW, 280 IPM,
High Tensile Strength (48,350 PSI)

type weld configuration. The minimum heat input that was achieved was 16.8 KJ/in/in at 75 IPM welding speed and maximum power (10.5 KW onto the work). Figure 25 shows the weld parameter data on 1/2-inch material and the relationship to energy input.

4.2.4 Analysis of Narrow Weld Phenomena

An understanding of the phenomena which produced the narrow, more efficient weld at high effluent gas flows is essential to the future application of this parameter to actual production welding. In tests defined in this work, control and reproducibility of the weld characteristic was very difficult, particularly on heavier material. Since only very minor input flow volume variations caused large variation in weld appearance, an obvious need is improved instrumentation to provide more direct knowledge of the effluent gas flow from the gun.

To gain a better insight into the actual phenomena, a series of welds were sectioned through beam cut-off points. It had been observed while conducting the weld tests, that the weld surface in this area had unusual characteristics which varied considerably in appearance, dependent on the gas flow conditions employed. A test series at 7 KW, 140 IPM and 1/8-inch work distance was produced at various gas flow conditions to provide variations in weld configuration from the normal nail-head type weld to a heavily undercut surface. Longitudinal sections shown in Figure 26 show that the remaining face depression under the final beam cut-off point becomes greater with increasing gas flow. The contours and flow appearance is mindful of a pressure-type effect which appears to be actually maintaining a deep hole in the work piece as the weld progresses. This effect could be related to increased beam efficiency or to a gas pressure jet impinging on the weld surface.

This appearance is even more clearly shown in Figure 27. These welds were made at a less than full penetration condition (8 KW, 280 IPM, 1/8-inch D_t). The lower gas flow weld, which in the transverse direction has the typical "nail-head" configuration, has only minor face depression under the beam, and a heavy line of centerline voids is being formed. A very slight increase in gas volume into the gun (3 CFH) forms a weld of different characteristics. The jet of gas coming from the gun forms a deep hole in the work. When this deep, and apparently continuously maintained, hole is formed, less transverse conduction can take place at the weld face and void entrapment cannot occur at the weld root.

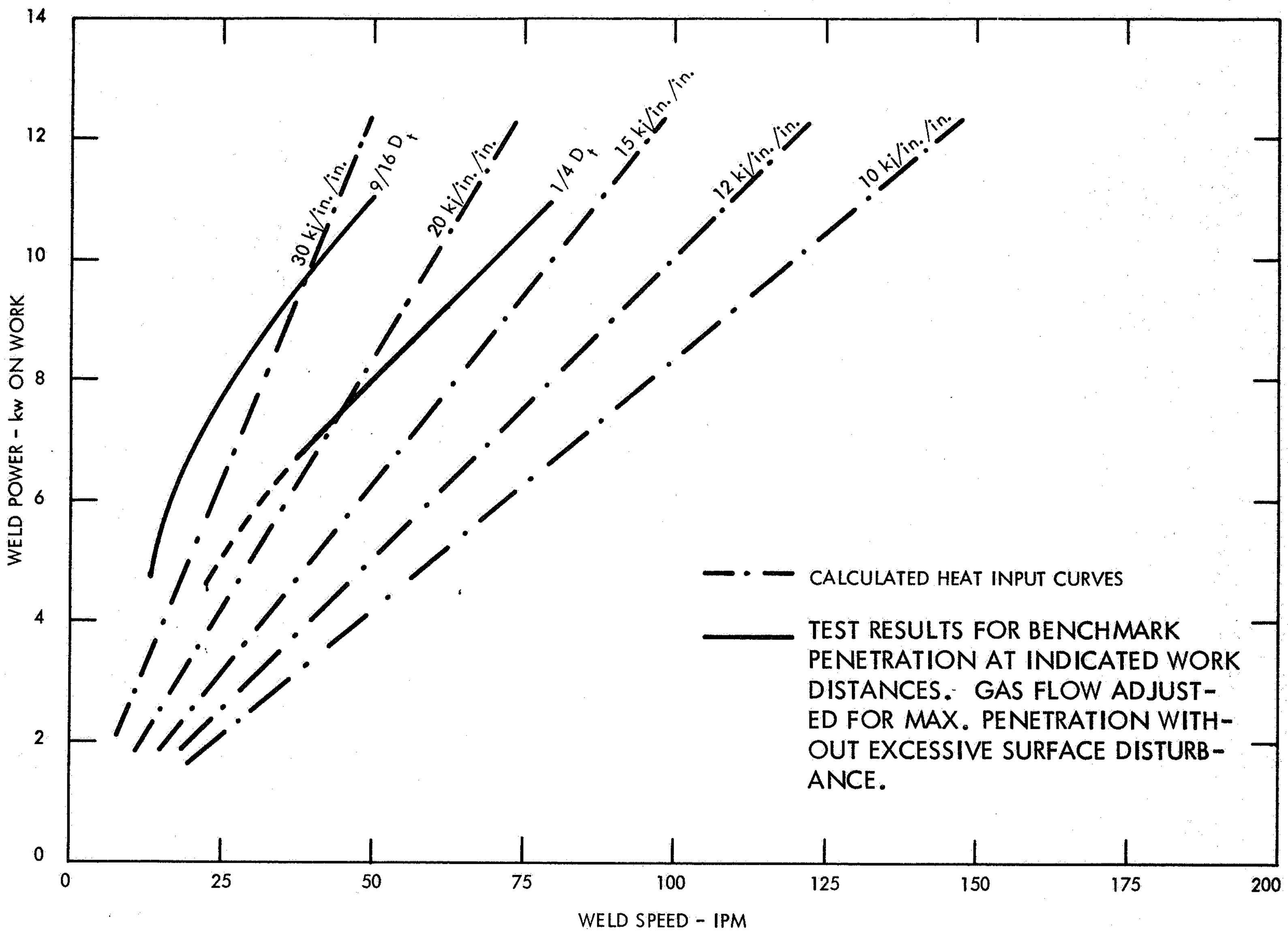
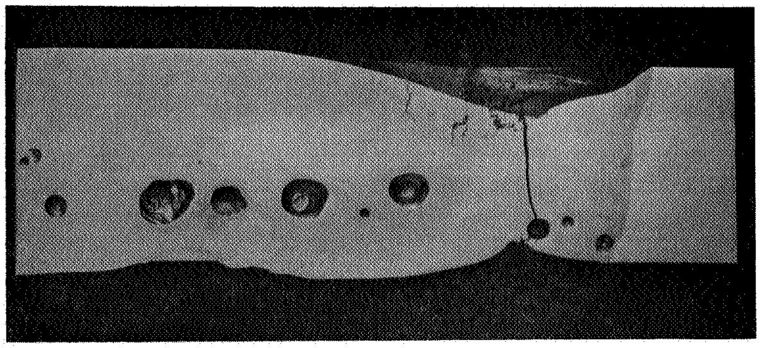
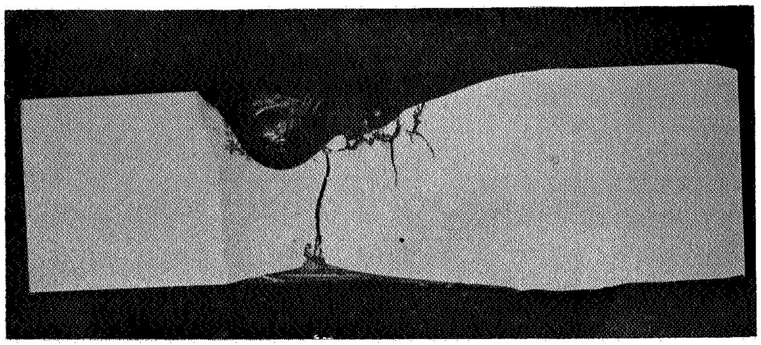


Figure 25. Weld Parameters Related to Heat Input, Bench Mark Penetration, 1/2 in. Material



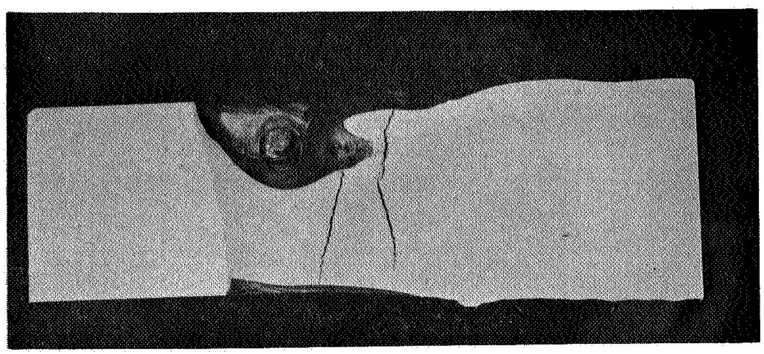
No. 541- 125 CFH Helium

4X



No. 542 -128 CFH Helium

4X



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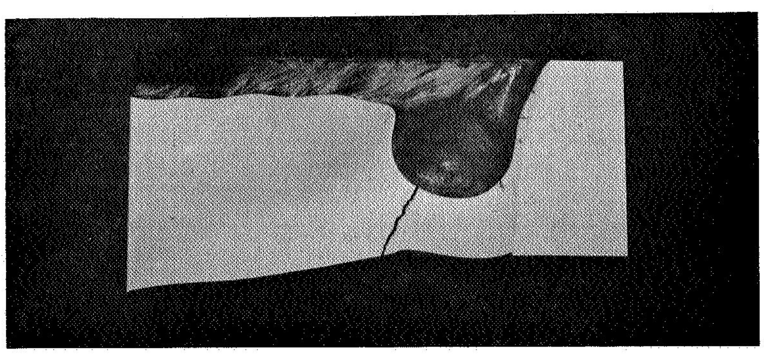
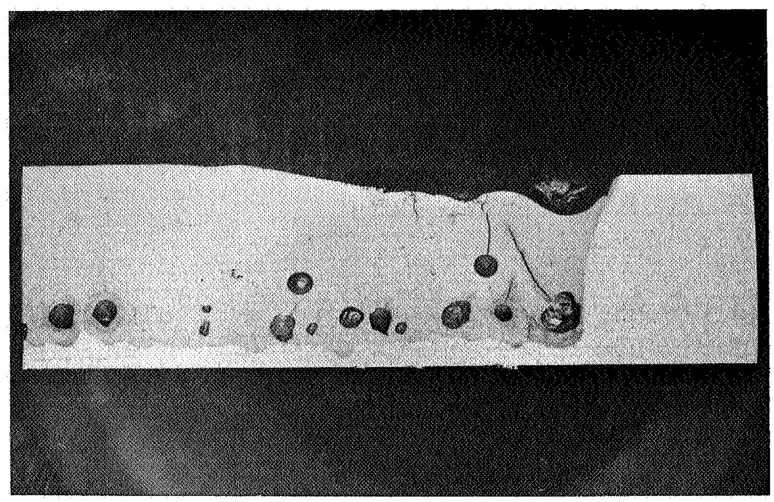


No. 543-132 CFH Helium

4X

Figure 26. Longitudinal Sections Through Beam Cut-off Points
Weld Conditions: 7KW - Transmitted Power, 140 IPM, 1/8 in. D_t

No. 551-129 CFH Helium



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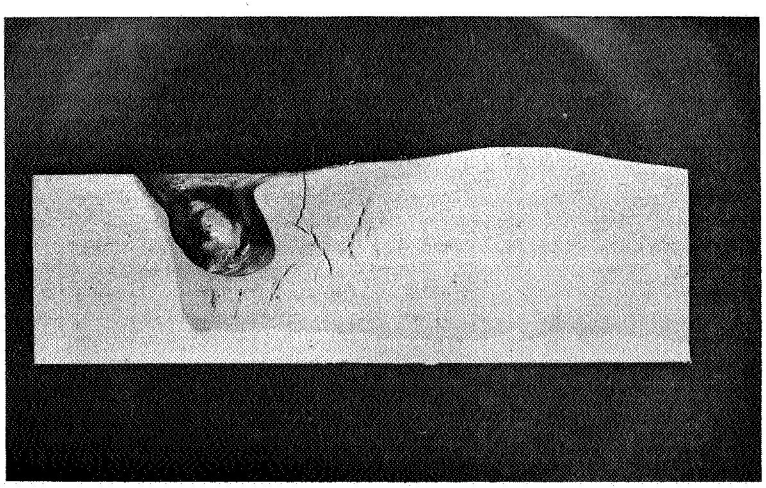

No. 550-132 CFH Helium

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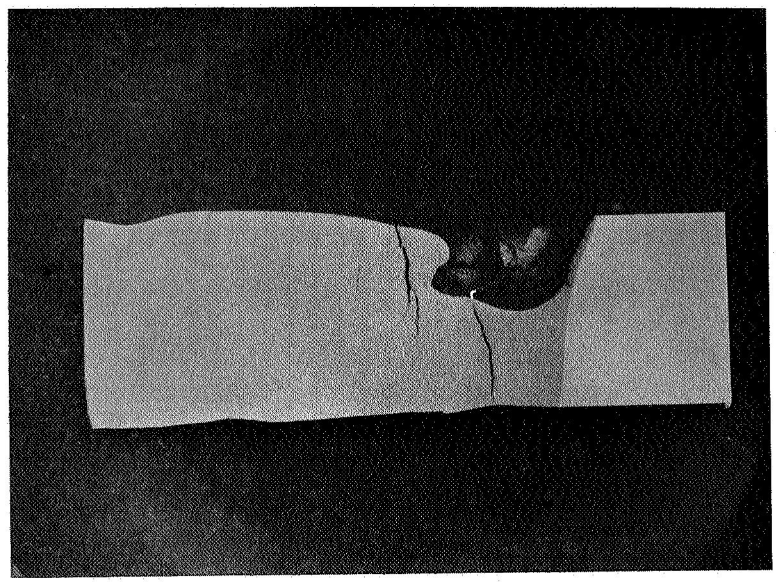
Figure 27. Longitudinal Sections Through Beam Cut-off Points
Weld Conditions: 8KW-Transmitted Power, 280 IPM, 1/8in. D_t

Full penetration welds at very high weld speeds show the same general effect. A deep hole is formed at the beam impingement point. Longitudinal and transverse sections are shown of typical beam cut-off points in Figure 28. The transverse section shows the minimum fusion on either edge of the hole. The molten material must then flow back into this depression.

While the analyses conducted provide some insight into the radically different weld configurations resulting from high gas flow conditions was far from complete, a number of factors were observed. A deep, relatively broad hole is definitely being formed at the beam impingement point. The presence of this hole reduces the void entrapment possibility in the root of the weld. The presence of the hole also limits the face width of the weld, particularly, and in this manner, may result in higher efficiency energy utilization. Continuous and uniform flow back into the hole which is present at high effluent gas flow is necessary to achieve smooth uniform weld surface finish.

No. 547-130 CFH Helium



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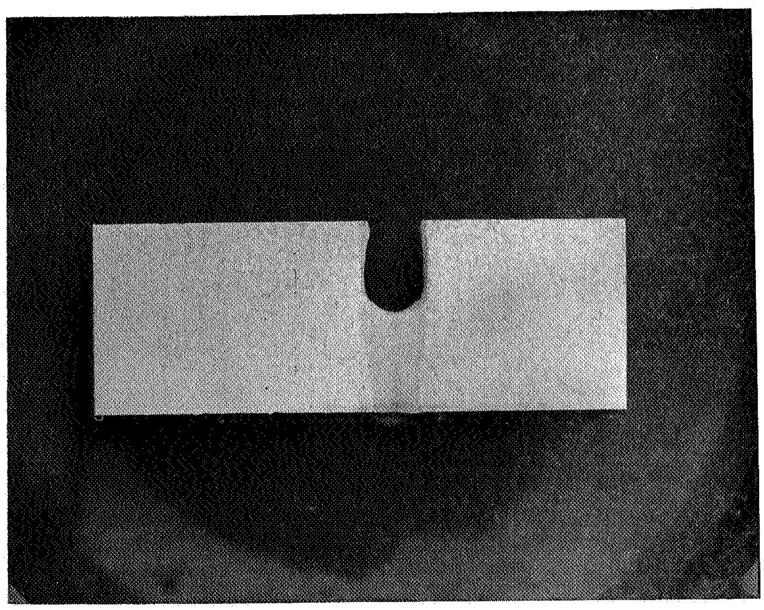

No. 548-130 CFH Helium

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Figure 28. Sections Through Beam Cut-off Points
Weld Conditions: 9.75 KW-Transmitted Power, 280 IPM,
1/8 in. D_t

5. TASK E - POROSITY OCCURRENCE IN HIGH SPEED WELDING

5.1 INTRODUCTION

The occurrence of porosity of various types over a variety of weld conditions suggested that hydrogen containing contaminants may not be the only source of defects in the Out-of-Vacuum Electron Beam Process. Extreme care in pre-cleaning, shielding technique, and parameter adjustment had not eliminated porosity or void formation unless changes were made in process speed - presumably to avoid trapping (but not avoid formation of) porosity.

To further establish the cause and possible means for eliminating porosity in the weldments produced at all speeds, a series of experimental studies were conducted. Welds were produced in a chamber with a vacuum and a high purity helium atmosphere to determine the effect of a known gas shielding quality. Solidification effects were also studied by making welds in 1100 aluminum (little or no solidus-liquidus range) and by welding with lead in and lead out angles between the electron beam and the work piece.

All of the welds produced to define the high speed parameters and weld configurations noted in the discussion of Task D were radiographically examined. The general effects on porosity level of the various conditions, and in particular the effects of gas flow, were evaluated.

5.2 RESULTS AND DISCUSSION

5.2.1 Welding in Chamber

Welds were produced in a small evacuation and back-fill type chamber attached directly to the bottom of the 10 KVA laboratory welder (see Figure 29). Welding could be performed in either a vacuum or controlled atmosphere using this setup. A small rotary type drive mechanism would revolve test material under the beam.

In producing welds in a helium atmosphere in this chamber, care was taken to assure an operational technique which would duplicate the normal out-of-vacuum welding procedure. This was achieved by using the normal gas flow into the gun as the back-fill and purge gas. By multiple evacuation of this chamber to approximately 1×10^{-5} mm Hg and back-filling with helium gas,interspersed with beam operation into a water-cooled copper block, moisture content of the

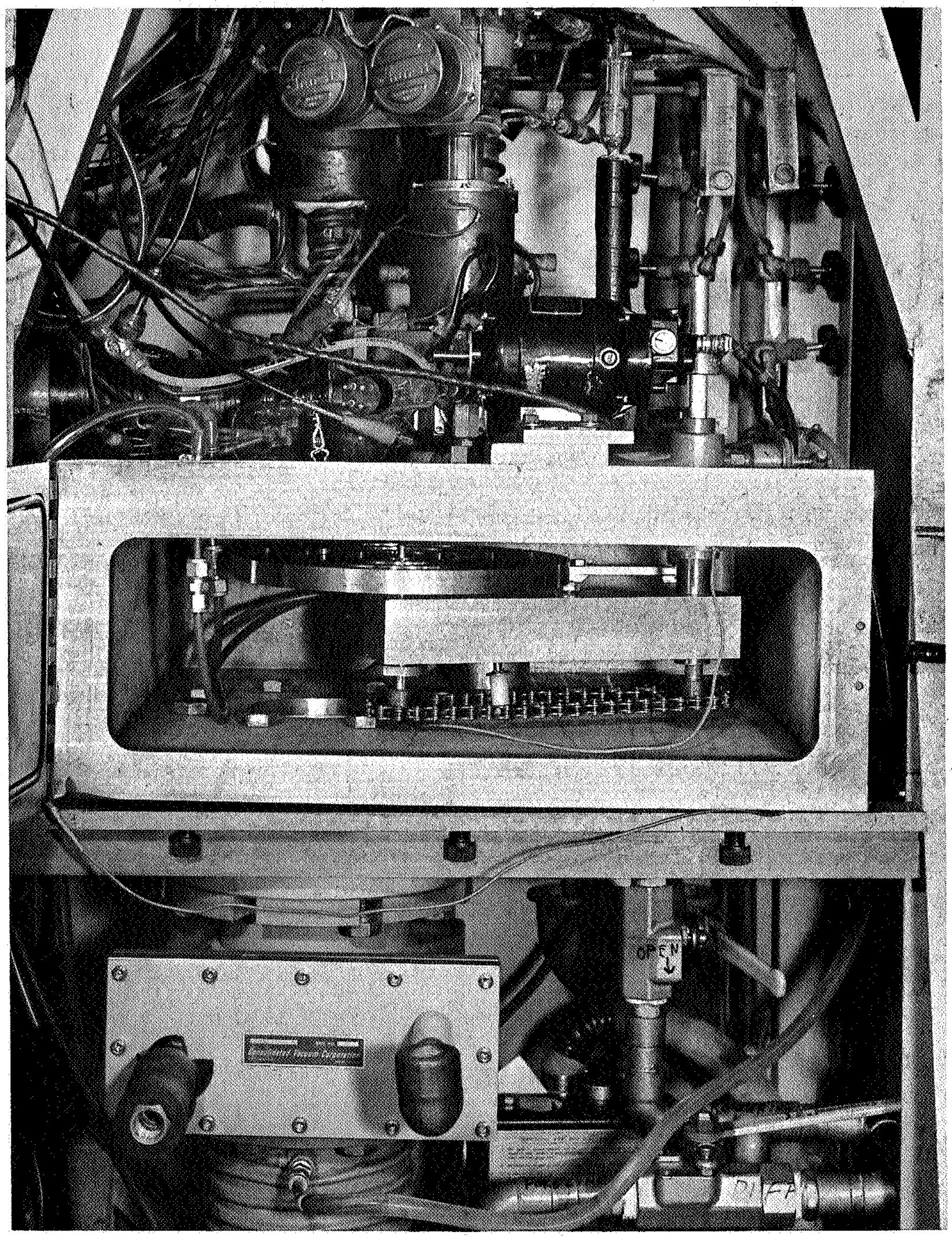


Figure 29. Welding Chamber Attached to 10 KVA Laboratory Out-of-Vacuum Welder

chamber could be reduced to approximately - 80° dew point during beam operation. The gas monitoring system could not be used during actual welding of the aluminum due to the evolution of metal vapor or smoke which contaminated the measuring device. All material to be welded was mechanically scraped on all surfaces immediately prior to placing it in the chamber to remove all surface contaminants which might be evolved by heating during welding.

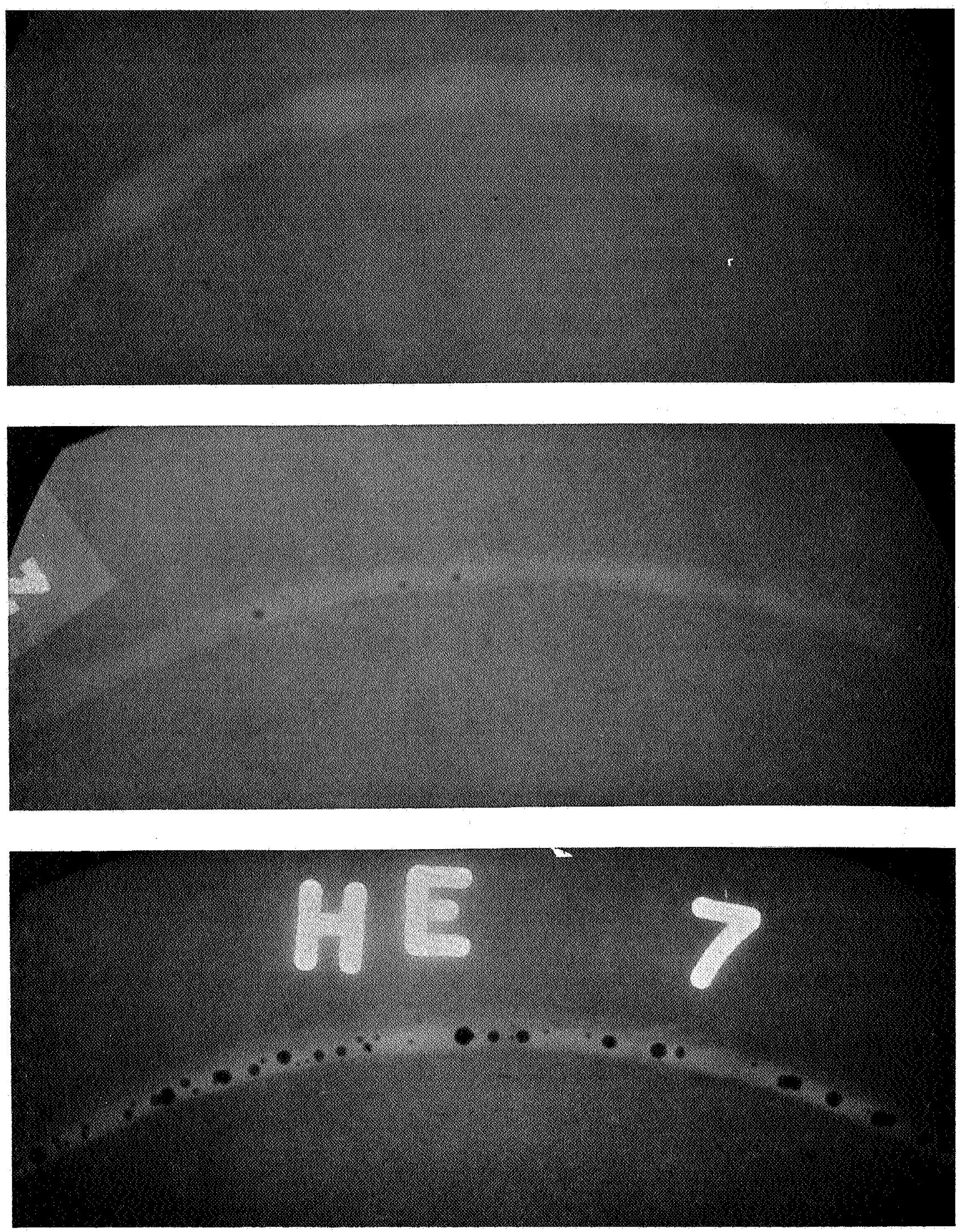
Welds were produced in 1/4-inch material in the chamber at power levels and speeds similar to that employed in previous work. At 3.6 KW gun power, the welds produced were similar in configuration to those made under normal procedures. Porosity occurrence was low and similar to the weld quality previously observed.

At higher power (6 KW), the welds were also similar in configuration and porosity occurrence. Radiographs of a series of welds produced in the chamber at speeds which provided varying amounts of penetration at this fixed power level are shown in Figure 30. It can be seen that at speeds less than bench mark (an excess penetration condition) porosity was not present upon solidification. As soon as the bench mark speed was approached, large center line porosity began to appear. This condition became very severe on less than full penetration welds. All these chamber welds which contained porosity were produced under closely controlled atmosphere conditions with minimum contamination.

The porosity that was observed is very similar to that which occurred at the same speed and energy levels for normal out-of-chamber welding. To confirm that these defects were related to welding in an atmosphere and not related to beam fluctuation or disturbance, a series of experimental joints were produced in a vacuum environment. A welding power level was selected which provided operating speeds comparable to those used in the helium atmosphere. The conditions were 2 KW and 40, 50, or 60 IPM speed, and samples were produced at 1/4-inch and 1/2-inch work distance. These joints made in vacuum were completely free of porosity regardless of penetration level as shown by the typical radiograph in Figure 31.

5.2.2 Welding of 1100 Aluminum

Alloys of aluminum and copper in the composition range approximating the 2219 alloy have a liquidus-solidus temperature range of approximately 150°F. Since the results of the



No. HE 11
50 IPM
Heavy
Penetration

No. HE 10
60 IPM
Slightly
Excess
Penetration

No. HE 7
70 IPM
Bench Mark
Penetration

Figure 30. Out-of-Vacuum Electron Beam Welds Produced in Controlled Atmosphere Chamber. 1/4 in., 2219-T87 Plate. 6 KW I_p, 5.2 KW on the Work, 1/4 in. Work Distance, 9 PPM H_2O.

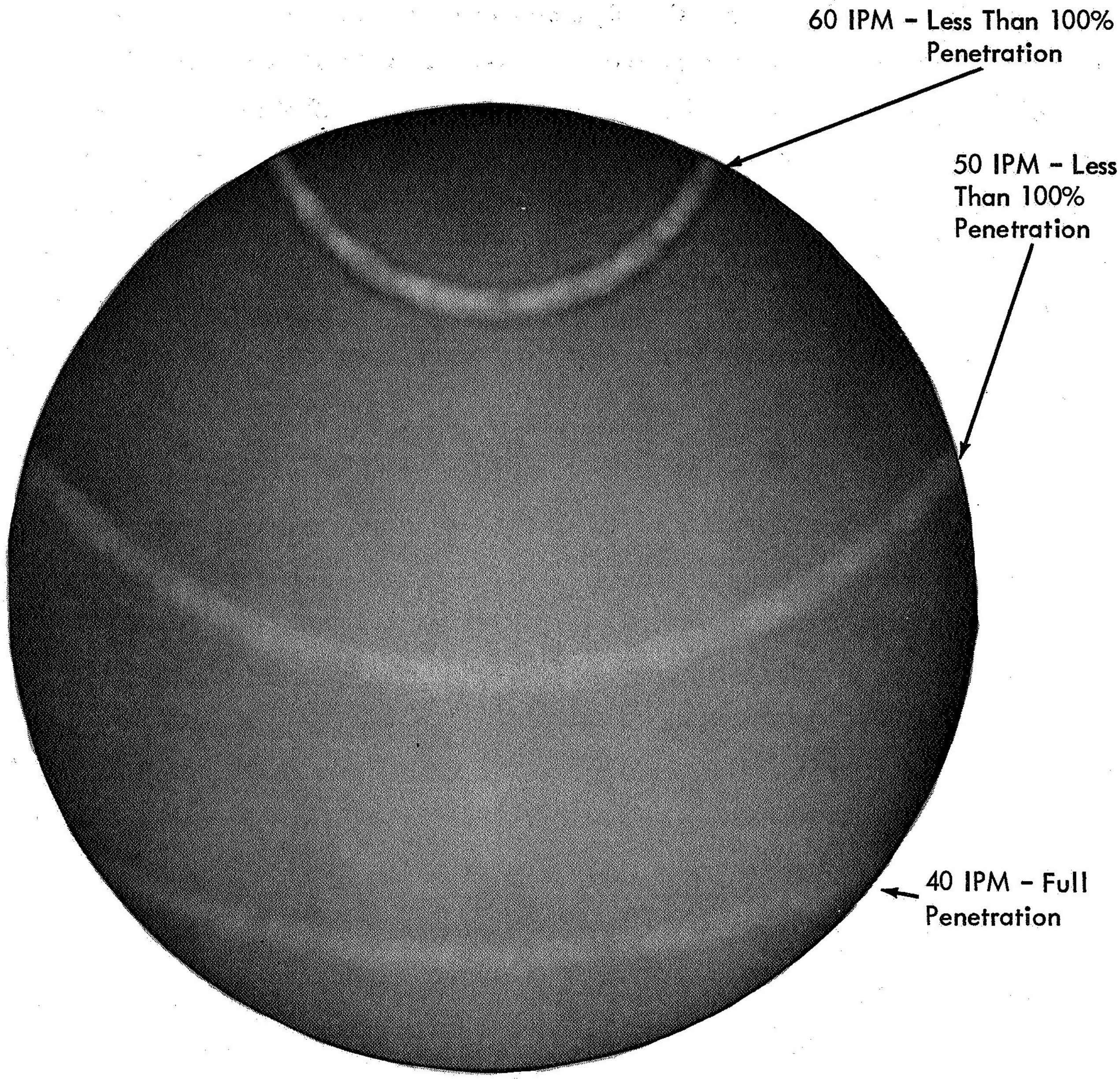


Figure 31. Vacuum Electron Beam Welds Produced with the Out-of-Vacuum Welder
1/4 in. 2219-T87 Aluminum, 2 KW, 1/4 in. Work Distance

chamber tests indicated that the porosity might be entrapped voids due to high weld speed (thus fast chill rates) and possible weld metal turbulence related to the gas atmosphere, it was theorized that a material of similar thermal characteristics to the 2219 but a narrower liquidus-solidus might provide more possibility for entrapment. A longer molten or semi-molten weld puddle,as would occur with 2219 aluminum, may give a lesser possibility for entrapment than a smaller, more rapidly solidifying one, as would occur with 1100 aluminum. Weld tests did confirm that for comparable weld speeds more severe porosity was present in the 1100 aluminum welds. Figure 32 is a radiograph of a typical weld produced in this material at 50 IPM. The porosity increase is clearly evident as compared to the 2219 welds made at comparable speeds shown in Figure 30.

5.2.3 Lead In and Lead Out Angles

In an effort to modify solidification patterns, both lead in and lead out angles between the gun and work piece were evaluated. To facilitate producing this angle, and also in an effort to improve general accessibility of the gun to the work, a pointed orifice system (120° included angle) had been developed by Westinghouse. This new orifice system used in both the normal and angled positions (20° max) produced welds of similar configuration and heat input values. Porosity, as revealed by radiographic examination, was also very similar under all combinations of speed and energy to that shown previously.

5.2.4 High Speed Welding

The primary purpose in producing the several weld series discussed in Task D was to study weld power and speed and the relationship to heat input and weld configuration. Thus, on many of the welds little or no precautionary measures, such as pre-cleaning and gas shielding, were utilized to limit or eliminate porosity. All welds were radiographically examined, however, and evaluated semi-quantitatively to determine if any significant trends were apparent. A number of characteristics could be observed. First, and perhaps most obvious, was the fact that welds produced at 9/16-inch gun to work distance with higher effluent gas flow conditions in the gun had a reduced porosity content. Further, at higher speeds and weld energy conditions than had been previously explored (7 KW and 120 IPM),porosity became scattered throughout the weld.

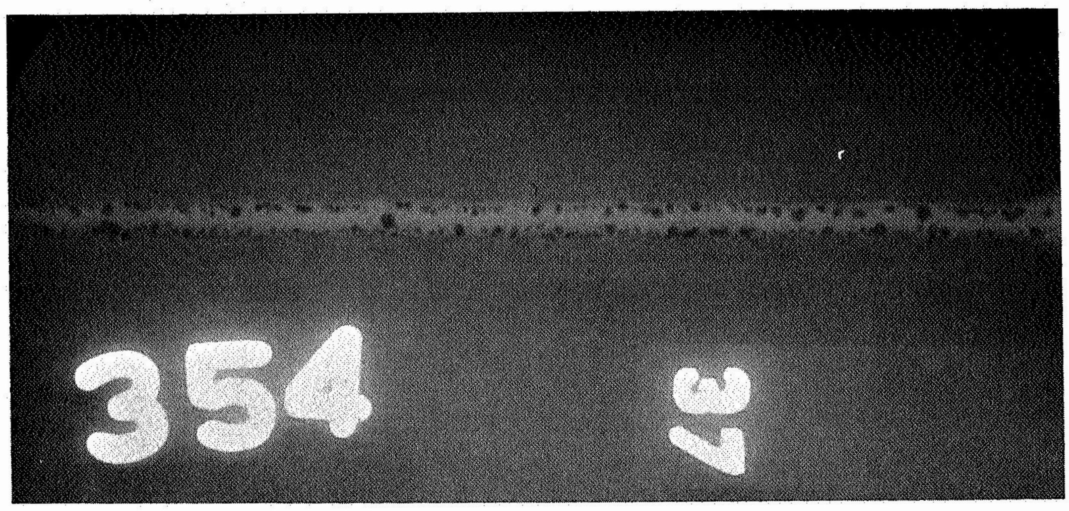


Figure 32. Out-of-Vacuum Electron Beam Weld in 1/4 in. 1100 Aluminum Plate
7 KW - I_p, 5.4 KW on Work, 9/16 in. Work Distance, 50 IPM Weld Speed.
Slightly Excess Penetration

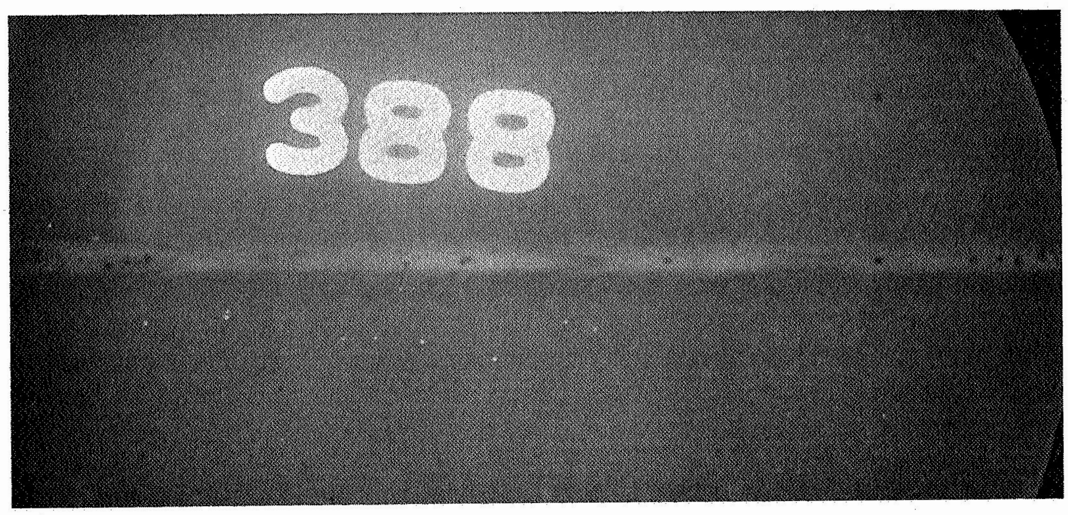


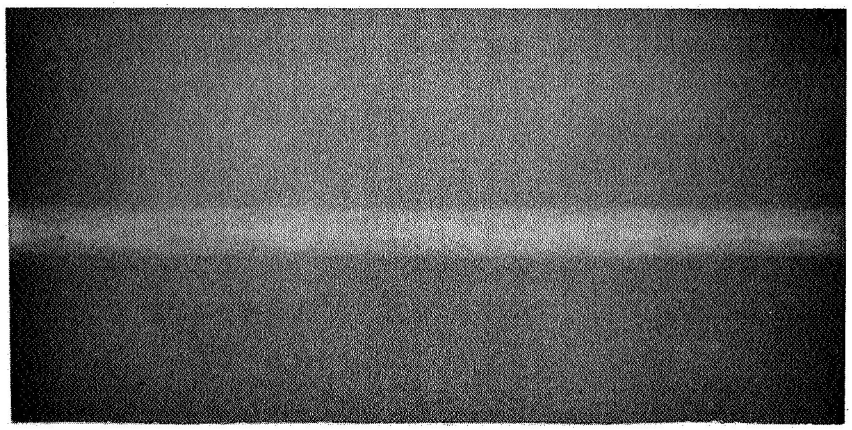
Figure 33. Out-of-Vacuum Electron Beam Weld in 1/4 in. 2219-T87 Aluminum.
Low Effluent Gas Flow. This is the Typical "Nail Head" Configuration

In earlier tests as energy and speed were increased up to the 7 KW - 120 IPM level, increased heavy center line porosity had occurred. It was this type of porosity that was proven unrelated to contamination by test welding in a controlled atmosphere chamber as noted earlier. One final observation was that gas backup did have a beneficial effect on the very high speed welds.

Subsequent tests in which shielding and pre-cleaning were employed confirmed these results. Figure 33 is a radiograph of a weld produced at 240 IPM and 1/8-inch work distance. The finer scattered porosity is a distinct improvement over the results obtained at the intermediate speeds and shown in Figure 30.

Inspection also indicated that porosity-free welds were obtained with a high gas flow into the gun when operating at high power (10. 5 KW on the work) and 9/16-inch work distance. These welds, made at 150 IPM, visually appeared to be the normal nail-head configuration weld with a relatively wide top surface. Figure 34 shows the typical radiographic quality of joints made with these conditions and the weld cross section. As can be seen, the fusion zone was not the typical nail-head type as expected but had a uniform width zone inward from the weld surface.

The most significant radiographic finding was made when the narrow, high efficiency welds made at short work distances and high gas flows were x-rayed. Radiographic examination of these welds indicated that these narrow, low heat input welds were free from porosity. This was true for weld speeds from 70 IPM to 280 IPM. Some representative results are shown in Figures 18, 19, 20, and 21 presented in Section 4 of this report which also show the highly desirable cross section that was achieved.



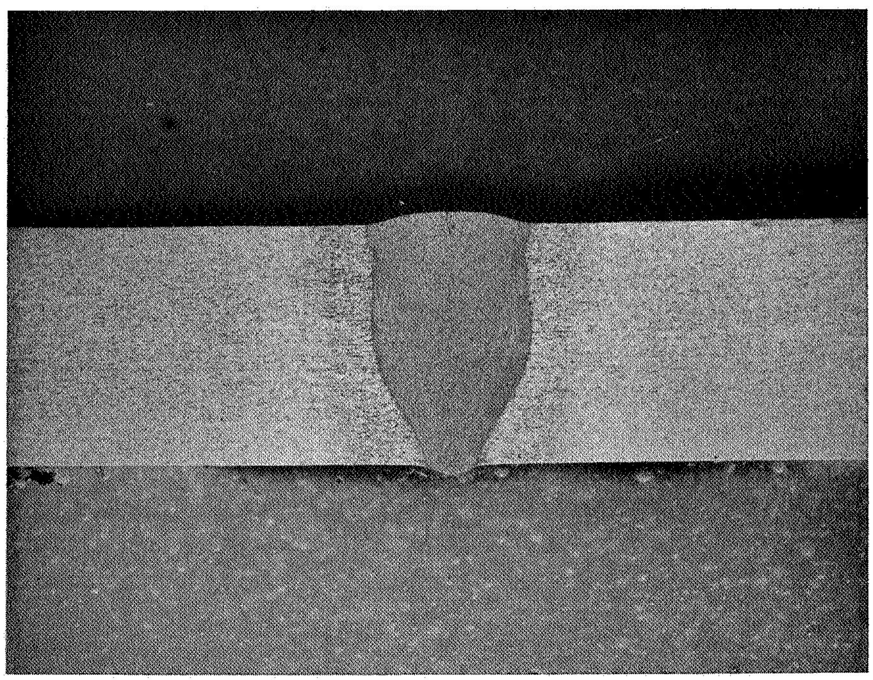


Figure 34. Radiograph and Weld Cross Section of a Typical Weld Produced at Long Work Distance (9/16 in.) and High Gas Flow.

6. CONCLUSIONS

Consistent pore free welds meeting ABMA-PD-R-27A, Class II requirements were produced at 45 IPM weld speed (27 KJ/in./in.) on .250 inch plate material. Tensile and bend testing were conducted on a series of these welds. Ultimate tensile strength was 42,000 in the as-welded condition and 40,000 with weld build-up removed.

Using maximum available power and short gun to work distances, the weld heat input on 1/4 inch material was reduced to 10.5 KJ/in./in. Aspect ratio on these welds was 1.6/1.

A study of the effect of effluent gas flows from the gun resulted in reduced heat input on welds in 1/4 in. material (8.4 KJ/in./in.) and aspect ratio of 2.5/1. Welds produced with this narrow weld phenomena were free of porosity.

Maximum tensile strengths of 49,000 psi were achieved on the narrow low heat input welds. Variations in strength at similar heat input on these welds were related to weld surface effects by metallographic examination.

Preliminary metallographic studies indicated the weld narrowing with higher gas flow was associated with the development of a deep hole in the work at the point of beam impingement. This hole is related to a pressure effect or improved beam density.

Control of the narrow weld phenomena was very difficult and it was not successfully applied to materials thicker than 1/4 inch.

The maximum weldable thickness, while maintaining a practical latitude in weld speed and energy control requirements, was 0.712 inches for the NASA-15 KVA welder.

Porosity could not be eliminated in welds in plate thicknesses over 0.500 inch within the scope of work on this program. Welding at very low speed (10-12 IPM) was necessary to reduce or eliminate porosity in the 0.500 inch plate.

Controlled atmosphere chamber welding demonstrated that voids occurred in welds produced at high speed even with closely controlled and monitored shielding environment. Porosity did not occur in welds produced in vacuum with the same equipment and at similar speed and penetration conditions.